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A Site Selection of An Energy Island in the North Sea: Optimal Location in an Ecological and an Economic Scenario Using a Multicriteria Decision Analysis (MCDA)

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Abstract

The Danish Government has decided to build an energy island, either as an artificial island in sand, concrete and steel or as a platform solution, in the Danish exclusive economic zone of the North Sea. The idea of the energy island is to connect offshore windfarms in the North Sea region to a central hub and re-distribute the wind energy to Denmark and its neighboring countries as the transition to a fossil free energy generation is being scaled up. The government has found a location in the North Sea Section East. However, the North Sea is known for its sand lance fish habitats which are critical to the local ecosystem as the sand lance is at the base of the food chain and the fish is prey for other fish, marine mammals and seabirds - some of which are vulnerable to commercial fisheries, offshore development and mining. To test whether the planned energy island would coincide with a sand lance habitat and to test if other alternative locations would be more suitable i.e. have a lower sand lance density, two other sections of the Danish North Sea were selected in this study. The other sections were the North Sea West and the Dogger Bank, both of which have good conditions like shallow waters and sandy sea bottoms. Furthermore, the study tested all sections in an ecological scenario with a focus on sand lance and an economic scenario with a focus on economic factors such as distance to shore and the wind resource. A so-called multicriteria decision analysis was used to give the different ecological and economic factors a weight relative to their importance. The two scenarios were compared to an equal weights scenario i.e. where all factors had the same importance. The multicriteria decision analysis used was the analytic hierarchy process (AHP). The North Sea Section East performed the best in both scenarios as the sand lance density here was within acceptable limits in an ecological perspective and the seabed, depth and windspeed conditions were acceptable in an economic perspective. The Dogger Bank was deemed non-suitable in both scenarios as the sand lance density was too high in an ecological perspective and the section was too distant from the shore and the windspeed was too low in an economic perspective. The study also concluded that an ecological scenario would not result in extra cable costs and an economic scenario would not result in a location with a high sand lance density. In fact, the North Sea Section East location would both have ecological and economic benefits.

Keywords: Ecology, Energy Hub, Energy Island, Geography, Geographical Information System, GIS, Multicriteria Decision Analysis, MDCA, Offshore windfarm, OWF, Site Selection.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AHP	Analytic hierarchy process
CR	Consistency Ratio

DEA	Danish Energy Agency
DFMF	Decreasing Fuzzy Membership Function
DKK	Danish Kroner
EBFM	Ecosystem Based Fisheries Management
EBM	Ecosystem Based Management
EEZ	Exclusive Economic Zone
ESM	Energy System Model
GIS	Geographic Information System
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IBTS	International Bottom Trawl Surveys
IFMF	Increasing Fuzzy Membership Function
MADM	Multi Attribute Decision Making
MCDA	Multi Criteria Decision Analysis
MODM	Multi Objective Decision Making
NSE	North Sea Energy
NSWPH	North Sea Wind Power Hub
NWA	Northwest Atlantic
OWF	Offshore Wind Farm
SI	Suitability Index
TSO	Transmission System Operator
UXO	Unexploded Ordnance
WLC	Weighted Linear Combination

List of Units

CPUE	Catch Per Unit Effort
GW	Gigawatt
km	Kilometer
km^2	Square kilometer
m	Meter
m/s	Meter per second

1. Introduction

The Danish government has decided to build an artificial energy island to connect offshore wind farms with the mainland grid and neighboring countries and thereby being able to collect and distribute energy. The energy island will be the first of its kind in the world and is supposed to be built in stages. Initially, it will have a capacity of 3GW scaled up to 10GW at a later stage. The energy island will be located in the North Sea off the Danish west coast some 100 km west of the town of Thorsminde (Danish Energy Agency, 2022).

The main objective for this is to reduce the dependence on fossil fuels (oil, coal, and natural gas) that are causing climate changes due to carbon emission and promote carbon free sustainable energies such as wind power generation. Another objective is to secure reliable energy distribution in combination with solar energy, biofuels etc.

Furthermore, Denmark has made an agreement as of 18 May 2022 with its neighboring countries about developing the North Sea into a large-scale green power plant consisting of multiple offshore wind farms and energy islands. Apart from generating electricity to end users, the offshore wind energy will also be used for electrolysis to make green hydrogen fuels such as methanol, ethanol and ammonia (Danish Energy Agency, 2022).

Some research has been made on offshore hub and grid designs describing technical and economic aspects (Konstantelos et al., 2017; Strbac et al., 2014; Gea-Bermúdez et al., 2020; Houghton et al., 2016; Fernandéz-Guillamón et al., 2019; Martínez-Gordón et al., 2021). However, an artificial energy island with connecting offshore windfarms (OWFs) and its impact on environmental factors such as the ecosystem (fish, marine mammals, birds etc.) is still very novel and has not been addressed thoroughly in the literature.

COWI, a Danish engineering company, has on behalf of the Danish Energy Agency (DEA), initiated a fine screening of potential offshore wind farm (OWF) areas in the North Sea. The screened areas are situated at existing and planned OWFs in proximity to the planned energy island. The fine screening is considering criteria such as *environmental factors* like residing and migrating seabirds, marine mammals (seals and porpoises), fish (breeding and spawning grounds) and *human activities* like ship routes, fisheries, ship dumping, existing pipelines and cables, old explosives at sea, sea archeology etc. COWI is using an approach giving the birds criteria the strongest importance (priority) (COWI, 2022).

The fine screening from COWI is representative and will partly function as foundation for an analysis of selecting an optimal site for an energy island in the North Sea, although the extent and geometry will be different from offshore wind farms. Moreover, the COWI screening only covers the area planned for OWFs and not the planned area for the energy island. As of January 3, 2024, the island design is still being considered (ENDK)[1].

The site selection of an energy island is of large interest as it is a novel concept in the form of an artificial island. It is being highly advertised in local media and it entails some potentials as it will be a flexible solution that can be added on to and contain, apart from cable connections and harbor buildings, other service functions such as staff facilities like hotel rooms, emergency room, datacenter, helipad, storages etc. It is also of interest as it will be relevant in future due to the transition from fossil fuels to green energy and energy security for western Europe, but, as mentioned earlier, both human and environmental factors come into play when planning a structure like an OWF or an energy island. One of the environmental factors is the loss of a habitat when an energy island about 1 km^2 at the seabed is taken away from the ecosystem. Especially the benthic fauna such as mussels, crabs and fish might be affected by this (Hutchison et al., 2020).

In a broader context, an optimal location is of vital importance as it could face severe consequences if the planning of the location is not done properly. The loss of habitat could lead to environmental effects i.e. it could disrupt the life of benthic fauna and fish on the sea bottom and thereby the food chain which could lead to migration or even extinction of certain species. This, in turn, could lead to societal effects such as downscaled fishing and affect its related industries e.g. food, fish meal etc. which again could lead to lack of self-sufficiency of fish products in a region and could compromise sustainable fishing as fish products would have to be imported from other regions of the world that do not comply with sustainable standards that restrict over-fishing and extensive use of bottom trawling for instance.

These problems might even be reinforced when considering large scale planning of OWFs and multiple energy islands, so-called cumulative effects, which is expected in the North Sea over the next decades and these effects are not fully understood (Bailey et al., 2014). Hence, the importance of an optimal location – or even broader, strategic planning of OWFs and energy islands in the North Sea is imperative.

The sand lance (*Ammodytes* sp.) is a fish that lives on and dwells in the sand bottom. It is at the base of the food chain and it is food for other fish such as cod and salmon, but also birds like puffins, terns, alks, seagulls and marine mammals like seals and porpoises. The loss of a habitat might have consequences for the fish, birds and marine mammals eating the sand lance and expel them from their natural habitat (Staudinger et al., 2020).

According to the 'Tænketanken Hav', a Danish Sea environmental think tank, "an ecosystem approach is an essential tool in the efforts to obtain a state of good environment". Further, "an ecosystem approach should first and foremost make sure that the utilization of the sea is done within the frame that supports a good state of environment objective and maintains it"

[1] ENDK is a transmission system operator (TSO) that owns, operates and develops all the transmission systems for electricity in Denmark and will act as a lessor of the energy island in the future (DEA, 2022).

(Tænketanken Hav, 2022). According to the latest report on the state of environment in the Danish seas, it is stated that the seas are vulnerable to impacts and still far from the goal of a good state of environment (Hansen et al., 2021). Thus, the planning of an energy island and surrounding OWFs involves two conflicting *objectives*: sustainable energy expansion and protection of the ecosystem.

In decision situations when dealing with conflicting objectives and their underlying criteria certain multicriteria decision analyses (MCDA) can be utilized to arrive at the best result i.e. an optimal site. Typically, the objectives and criteria are being ordered and/or weighted by their importance and then compared in pairs and the criteria can be visualized on maps. A strong importance will thus be reflected in a map layer and outperform a weaker importance in another map layer. That is, a strong importance (weight) on an *ecosystem factor* such as sand lance and a weak importance on an *economic factor* such as distance to shore will likely output a map (location) in favor of an ecosystem priority. In contrast, a strong importance on distance to shore (economic factor) and a weak importance on sand lance (ecosystem factor) will most likely favor the economic priority.

Suitability analyses have been widely used for OWF site selection during the last decades e.g., the Baltic Sea (Hansen, 2005), (Chaouachi et al., 2017), the Persian Gulf, Iran (Fetanat et al., 2015) and the Red Sea region of Egypt (Abdel-Basset et al., 2021). Similar to this study, Gerrits (2017) suggested a site selection model to determine the optimal location of a potential energy island and connecting OWFs ('Hub and Spoke Concept') at Dogger Banke in the North Sea. However, a suitability analysis to find the best location for an artificial energy island in the North Sea using an MCDA and a certain focus on the sand lance has, to the author's knowledge, not yet been undertaken – especially not when it comes to a comparison between an equal priority, an ecological priority and an economic priority. The fact that the artificial energy island is a study that compares three different sites to find the best location in a MCDA with a sand lance focus will make the study unique.

The aim of this study is to find an optimal site for an energy island by using a multicriteria approach in two different scenarios (an ecological priority and an economic priority) in a GIS environment compared to an equal weights scenario. An ecological priority will have an extreme importance on an environmental factor such as sand lance habitats and a moderate to strong importance on a factor like depth and little or no importance on distance to shore and proximity to a planned OWF. Conversely, an economic priority will have an extreme importance on windspeed and distance to shore, a moderate importance on proximity to a planned OWF, and an essential or strong importance on depth and little or no importance on sand lance habitats.

Finally, in an equal priority, the same importance will be assigned to all criteria in the analysis. Human factors such as visual effects criteria will be excluded from the analysis due to their distance from shore ~ 100 km. As a result of this study, it is expected that the potential negative impacts an energy island will have on the ecosystem can be mitigated i.e. mapping an optimal location that will have the least impact on the sea lance habitat and the local ecosystem. In addition, this study could contribute to a more ecosystem friendly planning of OWF facilities in a large-scale scenario in the North Sea.

1.1 Research Questions and Hypothesis

Research questions:

1. How different will the two scenarios (an ecological and an economic) be reflected in a MCDA compared to an equal weights analysis result?
2. Will an ecological priority result in extra cable length (cable costs)?
3. Will an economic priority result in a location with a high sand lance density?
4. What type of energy island structure (design) would be optimal for the identified location?

Hypothesis:

An *extreme* importance on sand lance habitats and a *moderately strong* importance on the depth attribute and *no* importance on distance to shore will change the planned location of the energy island significantly, i.e. a minimum of 20 km.

2. Background

2.1 Energy Island Concept

The notion of an energy island has been developed within the last decade. Van der Meijden (2016) describes an energy hub as a modular island in the North Sea that can be added on to according to increasing power demand. Such a hub would serve as a link between large-scale OWFs and the host country plus neighboring countries via interconnectors and would thus be a much more cost-effective solution for both operators and energy consumers compared to a traditional offshore grid with many redundant point-to-point connections. Van der Meijden (2016) proposes the Dogger Bank, an area in the North Sea, due to its shallow waters. An example of an energy hub is shown in Figure 1.

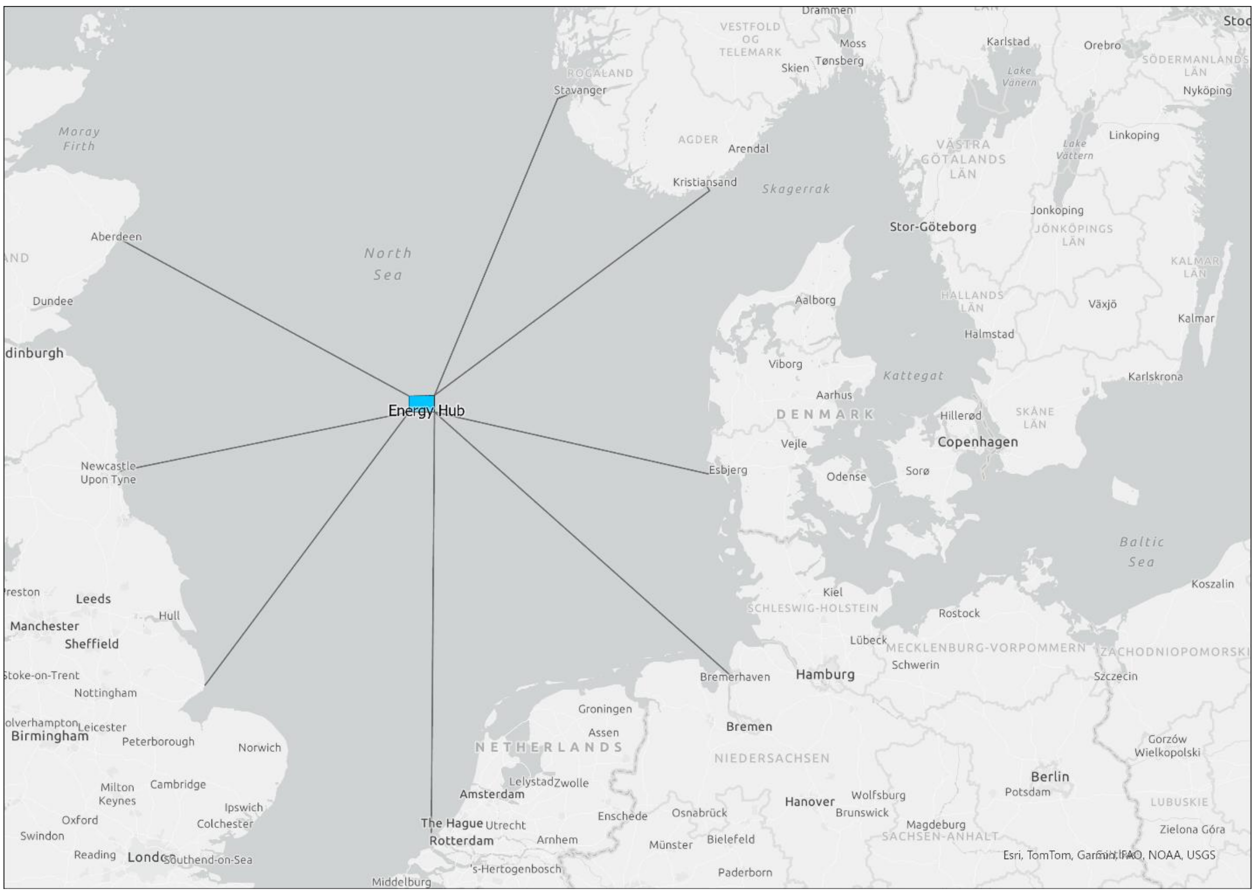

Figure 1. Offshore energy hub with interconnectors re-drawn by author (Inspired by van der Meijden, 2016)

Gerrits (2017) elaborates further on this notion in a feasibility study of the 'Hub and Spoke Concept' in the North Sea developing a site selection model to determine the optimal location of an energy island. Kristiansen et al. (2018) assess the power link island (PLI) which is an artificial island for transnational power exchange and distribution of offshore wind resources using an engineering-economic approach in comparison to a radial typology, that is, a traditional point-to-point connection. The added value of a fully integrated energy island solution is assessed using an optimization program for power system expansion planning under two future visions: Vision 1 with a low share of renewable power generation and Vision 4 with a high share of renewable energy power generation. The assessment showed significant cost savings in favor of a fully integrated energy island.

Fernández-Guillamón et al. (2019) present and discuss trends and perspectives of massive OWF integration into future power system, technical improvements of wind turbines and wind power plants such as capacity, power transmission to the shore e.g. high voltage alternating current (HVAC) and high voltage direct current (HVDC), their advantages and drawbacks, expected expansion of the OWF infrastructure in especially the North Sea and the Baltic Sea regions and other suitable areas in the US, China and India, power-to-x (P2X) conversion of surplus wind energy into other hydrogen substances such as ethanol, methanol and ammonia and subsea storage solutions. They also refer to the North Sea Wind Power Hub (NSWPH) consortium and the hub-and-spoke project i.e. a central island of some kind like a caisson island which is a concrete and steel construction, a sand island, a platform or a gravity-based structure which is a concrete structure sitting firmly on the seabed. Any of these will be linked to OWFs. The different hub alternatives are compared as far as water depth (m), construction time (years), size limit (GW), maturity i.e. level of development and reliability (middle-high) and footprint on seabed (low, middle, high) see Table 1.

Table 1. Types of hub structures and their specifications (Inspired by Fernández-Guillamón et al., 2019)

	Caisson island	**Sand island**	**Platform**	**Gravity-based structure**
Water depth limit (m)	< 25	< 40	< 45	> 100
Construction time (years)	3-4	6-8	3-4	3-4
Energy production limit (GW)	6	> 36	2	< 6 each wind turbine
Maturity	Middle	Middle	High	Units – High/ Linking Middle
Footprint on Sea bed	High	High	Low	Middle

Fernández-Guillamón et al. (2019) conclude that the hub-and-spoke project can facilitate the huge integration of OWFs in the North Sea and the total cost saving of this project compared to a common offshore wind power plant is significant and the construction time is estimated to be

more than ten years. Similarly, Jansen et al. (2022) assess the investment cost of an offshore wind power hub located at the Dogger Bank - 'Scenario Hub', versus a business as usual – 'Scenario BAU' that represents the current practice with point-to-point links. The study finds that the 'Scenario Hub' concept proves to be cost-competitive and cheaper compared to the current 'Scenario BAU' and, in fact, outperforms 'Scenario BAU' with more than 10GW connecting to the hub.
Dedecca et al. (2016) describe different typologies i.e. grid topologies ranging from radial solutions via hubs to a fully meshed, integrated typology (Appendix Fig. 25) stating that a meshed typology may increase the efficacy of energy transmission, system flexibility and reliability via interconnectors compared to a radial solution and thus requiring less investments and reducing offshore wind curtailment. Other non-monetary benefits of a meshed grid would include reduced environmental impacts of cable laying, increased competition and technical development.
Martínez-Gordón et al. (2021) emphasize the importance of increased spatial resolution and a higher temporal resolution in the map layers for energy planning, modelling and analysis and propose a modelling framework with the integration of GIS and the linking of different energy system models. An integrated modelling framework and a higher spatial resolution should thus be beneficial when analyzing energy systems e.g. large deployments of VRE[2] and their potentials based on the location, bottlenecks in the transmission grid, the balances between supply and demand on the energy markets and the improvement of the routing design of the energy infrastructure. Moreover, the North Sea Region (NSR) serves as a good example where spatial data with a finer cell size and more extensive time data would improve the energy planning, modelling and analysis.

2.1.1 Offshore Structures versus The Ecosystem

Bailey et. al. (2014) describe the potential and known conflicts of offshore development versus the ecosystem. Some of the so-called stressors that may impact the ecosystem are e.g. underwater noises from pile driving[3] when constructing the wind turbines and increased vessel traffic and could potentially cause hearing damage on particularly marine mammals and displacement of fish in the project area. This in turn could change the forage places for seabirds combined with a mortality due to collision with moving turbine blades.
A suggestion to reduce or eliminate pile driving is the emergence of floating wind power turbines. The floating wind structures are anchored to the seabed and designed for deep water areas where the water depth is greater than 50m (Appendix Fig. 26).
Bailey et al. (2014) emphasize the need for an assessment of the cumulated effects as the number and size of offshore structures increases worldwide. The assessment should entail disturbances

[2] Variable Renewable Energy (VRE).
[3] Pile driving: mounting of pile foundation onto the seabed.

during construction and operation of offshore structures, avoidance response of species i.e. displacement from key habitats and energetic costs, reproduction and survival rates and long-term impacts at the population level. The assessment should be set in context with other anthropogenic factors such as fisheries and exploitation.

Bailey et al. (2014) also suggest an improved future environmental impact assessment (EIA) and collecting of more detailed data i.e. longer time-series (temporal resolution) and finer-scale spatial resolution showing for instance interannual variability to identify the effects of construction which are critical for decision making. A finer scale spatial planning is especially important regarding sandbanks suitable for offshore development as it is also an important habitat for marine species and fisheries.

Frederiksen et al. (2004) also mention the decline of the black-legged kittiwake *(Rissa tridactyla)* which has declined by more than 50% since 1990 in the North Sea. The decline is mainly due to a reduced recruitment of its prey species, the sand lance (*Ammodytes marinus*) which in turn is linked to warm winters and local commercial fishery of the sand lance.

2.1.2 The North Sea Ecosystem

In a recent exploratory study about offshore structures and the ecosystem in the North Sea (Odinga et al., 2022, work package 4.1), the interaction between stressors and receptors[4] are described and different aspects of ecological value of offshore structures are discussed as threatened species and habitats in the North Sea are a key concern. The spatial scope of this study is the Dutch Continental Shelf (DCS) including Hub North, Hub West and Hub East (Fig. 3) and the temporal scope is seasonal or recent annual data.

[4] Stressors are factors of a system that can stress or harm the ecosystem. Receptors are those parts of the ecosystem that are stressed or affected by these factors.

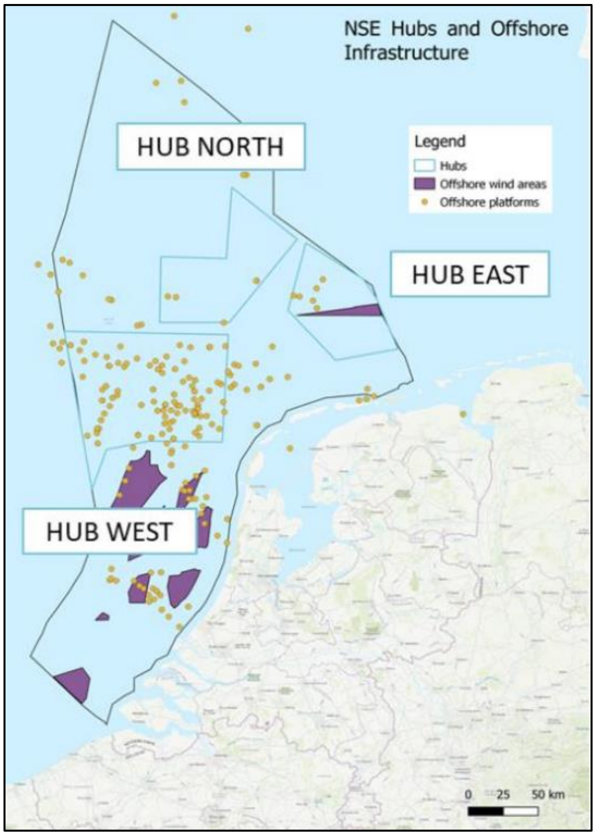

Figure 2. NSE Hubs and offshore infrastructure, The Netherlands (Reproduced with permission from Odinga et al., 2022)

The aim of the work package is to gain a better understanding of the ecosystem in the North Sea and to support decision-making for energy hub selection and their location. Furthermore, as many oil and gas platforms will be taken off the grid before 2050 due to the energy transition, decommissioning strategies such as the re-use of existing platforms, part-removal or abandonment of offshore structures are described.

In a food web (Fig. 3), trophic levels are used to define groups of species within the ecosystem distinguished through their food requirements. For example, phytoplankton is the base of the trophic levels and functions as a producer or prey for the next trophic level of consumers such as copepods, sprat and sand eels (aka. sand lances) which again are prey for the next level of predators such as plaice, mackerel, cod, rays etc.

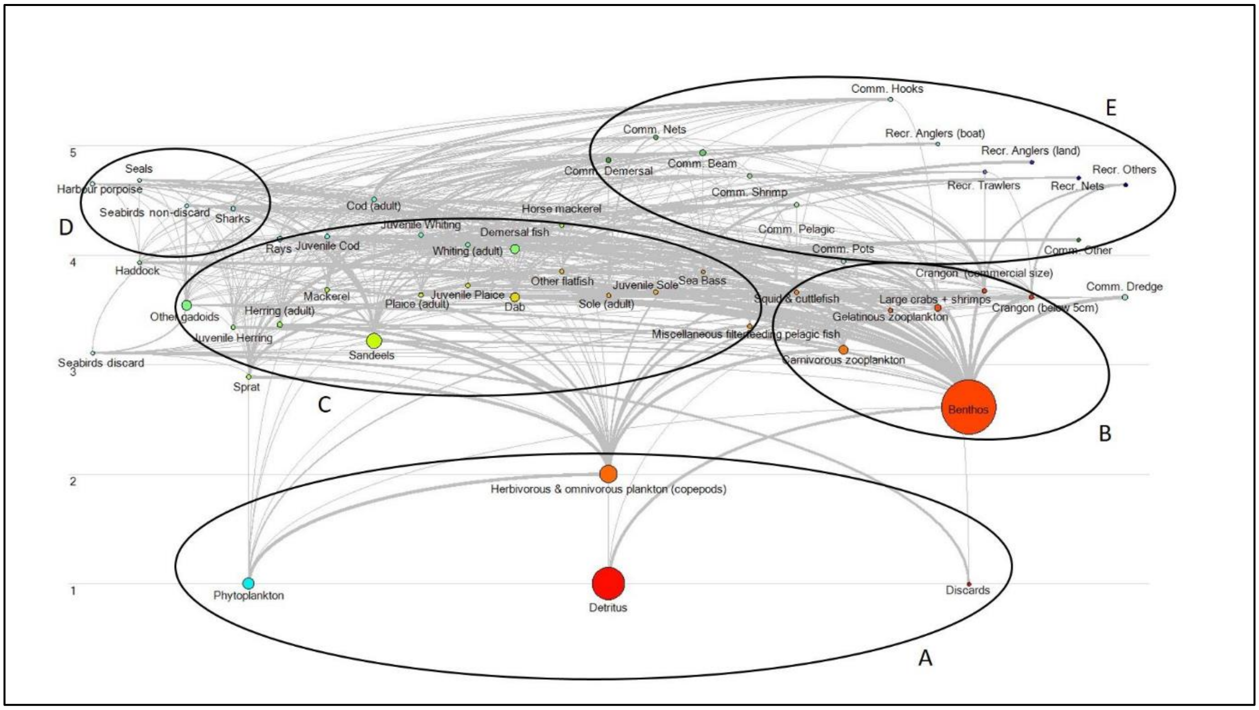

Figure 3. The North Sea food web (Reproduced with permission from Pint et al., 2021)

Fig. 3 presents an illustration of the southern North Sea food web and its interactions. The size of circles represents the biomass included in that functional group. The ellipses show related functional groups. A: The functional group at the bottom of the food web. B: The invertebrates in the food web with a trophic level higher than 2. C: Fish related functional groups in the food web. D: The top predators in the model have a trophic level between 4 and 5. E: The fishing fleet included in the food web (Primary source: Pint et al., 2021, Secondary source: Odinga et al., 2022).

The map layers in the NSE Atlas include a benthos layer, a harbor porpoise layer and seabird wind farm sensitivity index (WSI). Benthos are organisms that live on, in or near the bottom, for example shellfish, worms and crabs. The harbor porpoise is the most common marine mammal and a top predator in the North Sea and according to the literature (Bailey et al., 2014; Pint et al., 2021; Odinga et. al., 2022). The porpoise is largely disrupted by pile-driving activities during the construction of OWFs. The harbor porpoise is considered a key species and is protected by international law. The WSI is based on data from Leopold & Van der Wal (2021) which defines the mortality risks for birds due to collision with OWFs. The North Sea is a primary habitat for seabirds and the upscaling of OWFs and other structures pose a threat to the birds due to collision with the structures. The countries in the North Sea region are obliged to follow the international bird protection laws such as Natura 2000[5] when developing offshore structures.

[5] Natura 2000 is a coordinated network of protected areas for valuable and threatened species and habitats within the European Union.

Other layers are considered but not added or are still pending due to uncertainties and lack of suitable spatial data (as of 1 March 2024). These layers are primary production (phytoplankton, seaweed etc.), fish (demersal and pelagic fish[6] including elasmobranchs as sharks and rays) and other marine mammals such as minke whales and Atlantic bottlenose dolphins, grey and harbor seals. The study also describes decommissioning scenarios especially relevant for existing offshore structures in the North Sea which are about to end operational life (Appendix Fig. 27).
The scenarios are:

a) Re-use of an existing structure e.g. a former oil and gas platform changed to a wind power station and keeping the existing structure with the epifouling communities and foraging fish, marine mammals and birds.
b) Partial removal e.g. removing parts of a decommissioned platform and leaving remaining parts for the epifouling communities and foraging fish, marine mammals and birds.
c) Abandonment e.g. complete removal of structure including jackets, scour protections etc. which act as an artificial reef and returning to naked seabed.

The optimal decommissioning scenario can best be determined by local variables such as depth profiles, stand-alone structures or groups of structures, water salinity, hydrodynamics, existing ecosystem etc. However, the results from the literature and that study demonstrate that there is a potential ecological value of existing structures.
According to Odinga et al. (2022), a focus should be on assessing existing ecological values and potential cumulative effects[7] from the development of energy hubs including artificial islands as well as potential benefits from nature inclusive design[8]. Further, improved map data on benthos hotspots, elasmobranchs, future projections and modelled data should be added to the NSE Atlas when available as the atlas is being updated continuously.

2.2 Sand Lance in The Northwest Atlantic and The North Sea

The sand lance or sand eel (*Ammodytes* sp.), which consists of different subspecies e.g. *A. americanus*, *A. dubius, A. marinus, A. tobianus, H. lanceolotus* (henceforth sand lance), is known to live on and dwell in sandy sea bottoms to hide from its predators. It is at the base of the food chain and is a forage fish for other fish such as cod and salmon, but also birds like puffins, terns, razorbills, seagulls and marine mammals like seals and porpoises also eat the fish (Appendix Table 23).

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[6] Demersal fish live and feed on the sea bottom. Pelagic fish live and feed higher up in the water column.
[7] Cumulative effects are a combination of past, present and foreseeable future human activities, and natural processes.
[8] Nature inclusive design means that man-made structures e.g. a jacket or a scour protection of an offshore structure is designed in a way that it can attract benthic organisms and form a reef-like habitat.

The life of a sand lance starts as a fertilized egg spawned by a mother fish from fall through winter. The eggs are demersal and adhesive on a sandy substrate and are thought to develop during a couple of months. The larvae range from 4-7mm at hatch. After hatching, the larvae will live in the water column for the first 3-4 months until they reach sizes of 35-50 mm and settle into demersal habitats. Larvae consume phytoplankton in the first time shifting to copepods at a later stage. Although knowledge of the juvenile sand lance's population and biology is scarce, it is known from the literature (Holland et al., 2005; Wright et al., 2000) that the adult sand lance prefers coarse-grained sand from which they emerge on a daily and seasonal basis to feed in the water column. The food intake is characterized as large and energy-rich copepods, members of the genus *(C.finmarchius)* as well as other zooplankton. The adult length is typically between 15-20 cm (Rindorf, 2000).

According to Staudinger et al. (2020), there is some available data about the sand lances in the Northwest Atlantic (NWA) about their early and adult stages, but a significant lack of data of their juvenile stages and their first life as their slender bodies makes them difficult to catch due to mesh sizes used. The article particularly points out the lack of information about the population and distribution of the sand lance in the NWA. However, more data is available about the sand lance in the North Sea regarding mechanism of long-term decline in size and recruitment of sand lance is supplemented to the Staudinger team research (Frederiksen et al., 2011; Van Deurs et al., 2009).

The sand lance plays a very important role in the NWA and the North Sea ecosystems and like no other forage fish, it provides ecosystems services that directly and indirectly support humans like commercial fisheries of the sand lance itself for fish meal products, but also fisheries of its predators like cod, mackerel and salmon and a derived tourism. There are existing and emerging threats from climate change, fisheries, sand mining, dredging, energy exploration, offshore development and other human activities that may impact the sand lance population directly through harvest or habitat degradation or impact the food web relationships indirectly in a combination of the above factors. The above-mentioned stressors could have effects on the regional human-ecological system as it could cause a depletion of the sand lance and its predators and thereby affect the economies in the region. It would need certain attention, especially to avoid tipping points, in management and conservation initiatives as the consequences are not fully understood (Staudinger et al., 2022).

2.2.1 Sand Lance - A Forage Fish

Based on literature, observations (stomach contents) and other visual observations, the Staudinger article (Staudinger et al., 2020) finds that the sand lance has three major predator groups: fish, birds and marine mammals. Out of these, 45 species of fish, 2 squids, 16 seabirds

and 9 marine mammals in the NWA region are reported to consume sand lances as they provide a highly nutritional source of lipids and proteins to its predators.
Sand lances are found in the diets of several fish of high conservation concern e.g. Atlantic cod, Atlantic salmon, bluefin tuna etc. Results suggest that sand lances contribute substantially to their nutrition and could influence abundance, distribution and population recovery where they are depleted (Staudinger et al., 2020). In the North Sea, the sand lance is of certain importance to the Atlantic cod (Energinet, 2017). Totally 16 seabirds including terns, alcids, gulls, cormorants, murres, gannets and some ducks are reported to consume sand lances in sizeable amounts along the eastern coast of the USA and Canada according to database searches in Web of Science, Academic Search Premier and NMFS/NEFSC Food Web Dynamics Program database (Smith & Link, 2010; https://inport.nmfs.noaa.gov/inport /hierarchy/1368) performed by the Staudinger team (Staudinger et al., 2020). In the North Sea, the sand lance is of certain importance to terns, alcids and black-legged kittiwakes (COWI, 2022).
Sand lances in the North Sea are important prey for pinnipeds such as grey seals and harbor seals and small-sized cetaceans like the Atlantic white-sided dolphin and harbor porpoise. The sand lance is also prey for greater cetaceans like minke whales, which are frequent in the NWA and occurs occasionally in the North Sea (Staudinger et al., 2022; COWI, 2022; Energinet 2017).

2.2.2 Climate Change Implications

Another stressor for the sand lance is the rapid warming of the oceans including the NWA and the North Sea. The sand lance's primary prey, copepod, prefers cold water habitats between 2°C - 7°C during winter and spring season and 7°C - 15°C during the summer and fall season. A continuation of the warming may reduce the abundance of this and other plankton and thus affect the production of sand lances and other species in the food web. With reference to Frederiksen et al. (2011), studies from the North Sea has found that the sand lance has partly replaced its main prey copepod (*C. finmarchicus*) by a warmer conspecific *C.helgolandicus* due to the warming. The warming of the oceans may also have other implications such as acidification and differences in circulation flows (Staudinger et al., 2022) that may affect the sand lance negatively.

2.2.3 Fisheries

Commercial fisheries on sand lance are practiced in different parts of the world. The sand lance is primarily used for oil and fish meal production. There are no large-scale commercial fisheries on sand lance in the NWA due to regulations. However, it is allowed in the North Sea under certain regulations. As of 18 April 2022, 83,123 tons of the fishing of sand lance are allowed in the North Sea and neighboring waters Skagerrak and Kattegat off the coast of Denmark (EU zone) but banned in the Norwegian zone for the time being (Danish Fishing Board, 2022).

As the abundance of sand lance in the North Sea is fluctuating from year to year, the commercial fisheries are subject to a regulatory system that annually restricts or de-regulates the harvesting of sand lance according to the current population size.

Fisheries are conducted with a bottom trawl gear i.e. a fishnet that is being pulled by a vessel scraping the sea bottom for sand lances and other fish. This method has been highly criticized not only due to depletion of the sand lance but also to the disruption of the sediment, benthic species, eggs and larvae residing in and on the sea bottom (Danish Nature Conservation Association, 2022).

2.3 Energy Development and Resource Extraction

Offshore construction, dredging and resource mining are stressors that may impact the sand lance population. Offshore projects like caisson energy islands will inevitably have a significant footprint on the seabed as a part of the habitat will be used for construction (Fernández-Guillamón et al., 2019). However, the offshore structures may also have the possibility to become an artificial reef habitat that supports hard-bottom associated communities that sand lances rely on in case the offshore constructions are combined with restricted vessel traffic and fisheries especially with bottom trawl gear (Lindeboom et al., 2011).

As more devastating floodings and storms are expected and to avoid sea level rise, offshore sand mining may increase due to the need for substrate to replenish and elevate beaches and curb erosion. Nevertheless, the mining is likely to disturb sand lance production as the sand lance eggs and the older individuals are stuck to or buried in the sand sediments which may result in decreased production of the sand lance and higher trophic level predators.

On the other hand, some development activities in the North Sea have shown neutral or even positive short-term ecological benefits, such as increased juvenile sand lance abundance before and after construction of wind turbines (Leonhard et al., 2011). These benefits are mainly ascribed to improved or neutral sediment quality, reduction in predators and reduction in fishing activities during the construction phase or a combination of these. However, no long-term effects on sand lances are seen in that area despite an increase in species diversity due to the artificial reefs effect (Leonhard et al., 2011).

2.4 Ecosystem-Based Management Approaches (Restrictions and Possession Limit)

The sand lance also provides so-called ecosystem services[9] as it is a condition for higher trophic predators which contribute to regional economies, food resources and recreational fishing, tourism etc. (Nelson et al., 2013). To protect a healthy ecosystem and ecosystem services for the

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[9] Ecosystem services are natural processes that human beings can benefit from e.g. fresh air, water, food, tourism etc.

next generations ecosystem-based management (EBM) and ecosystem-based fisheries management (EBFM) plans are being implemented in the USA, Canada and the EU through policies and regional planning. These plans are supposed to account for direct and indirect human interaction with the marine ecosystem, assess the ecological risks and cumulated effects based on current knowledge. The EBM should include stakeholders from different fields e.g. government representatives, companies, scientists etc. EBM can restrict fisheries on threatened species and ban or restrict offshore mining and construction if needed. If a construction gets permission, the environmental impact should be monitored during and after construction (Tænketanken Hav, 2022).

2.5 Multicriteria Decision Analysis (MCDA)

When dealing with a decision situation e.g. finding the best site for an offshore energy island, usually different interest groups (stakeholders) are involved for instance governmental representatives, scientists, environmentalists and parties affected by a decision. Each group brings along different criteria related to the overall objective (goal) like building an energy island. Often the stakeholders have different and conflicting criteria that can make it difficult to come to an agreement. The criteria for one group could for instance be the maximization of production and minimization of costs and for another group strong environmental protection and a limited human impact on the environment.

To reach a mutual compromise, reduce bias, group thinking failures etc., a multicriteria decision analysis (MCDA) can be a tool to aid a complex decision problem that leads to a more informed and better decision. MCDAs are different techniques and procedures for structuring decision problems and designing, evaluating and prioritizing alternative decisions (Malczewski, 2006).

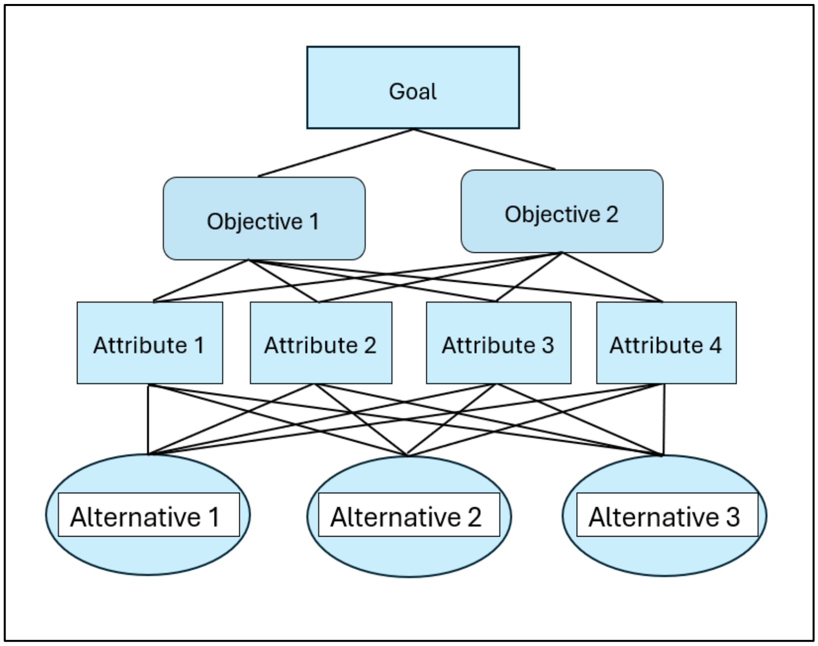

Figure 4. MCDA model hierarchy (Inspired by Malczewski and Rinner, 2015)

A multicriteria decision analysis technique can have a hierarchical structure (Fig. 4) e.g. a goal (overall objective) at the top, criteria (sub-objectives or attributes) below the goal and decision alternatives at the lowest level. In short, an overall objective or goal could be a planned energy island in the North Sea, the sub-objectives could be cost efficiency vs. ecosystem. Each sub-objective requires attributes that are quantifiable i.e. they can be measured. Examples of attributes could be building costs, sea depth, seabed substrate and distance to shore.

Decision alternatives are choices e.g. different locations which are to be evaluated on a set of criteria i.e. attributes or sub-objectives. Each level in the hierarchy is linked to the next-higher level, so that each decision alternative is being evaluated based on the criteria higher up in the hierarchy and will thus define the resulting solution (goal).

The sub-objectives and attributes may have weights assigned to them defining their relative importance i.e. the cost-efficiency objective may be assigned the value of 0.33 and the ecosystem objective a value of 0.67 as it is being judged two times important as the cost objective. Similarly, the underlying attributes will be assigned weights as well. The weights will add up to 1.00 on each level. The weight will thus reflect the importance in a final rating map where the alternatives can be ranked from most suitable to least suitable. The most suitable alternative is then likely to be the selected (Malczewski, 1999).

It should be emphasized that several modifications of MCDA techniques exist e.g. different objectives can be analyzed separately i.e. where an ecological objective is evaluated in one MCDA and an economic objective is evaluated in another and then both objectives will be compared afterwards.

3. Data and Materials

3.1 Study area

The focus will be on the proposed energy island area in the Danish section of the North Sea, an adjacent area next to the proposed section and an area further out in the North Sea, but within the Danish EEZ[10]. The proposed energy island is expected to be built in the *North Sea III East* section (henceforth the *East*) (DEA, 2022; Dataforsyningen, 2022). The proposed site in this area will serve as a reference for the two other potential sites in the study area, *North Sea III West* (henceforth the *West*) adjacent to the *North Sea East*, and the Danish section of *Dogger Bank*. Figure 5 shows the complete study area including the proposed energy island and the landfall point where the cables are expected to meet the mainland of Denmark.

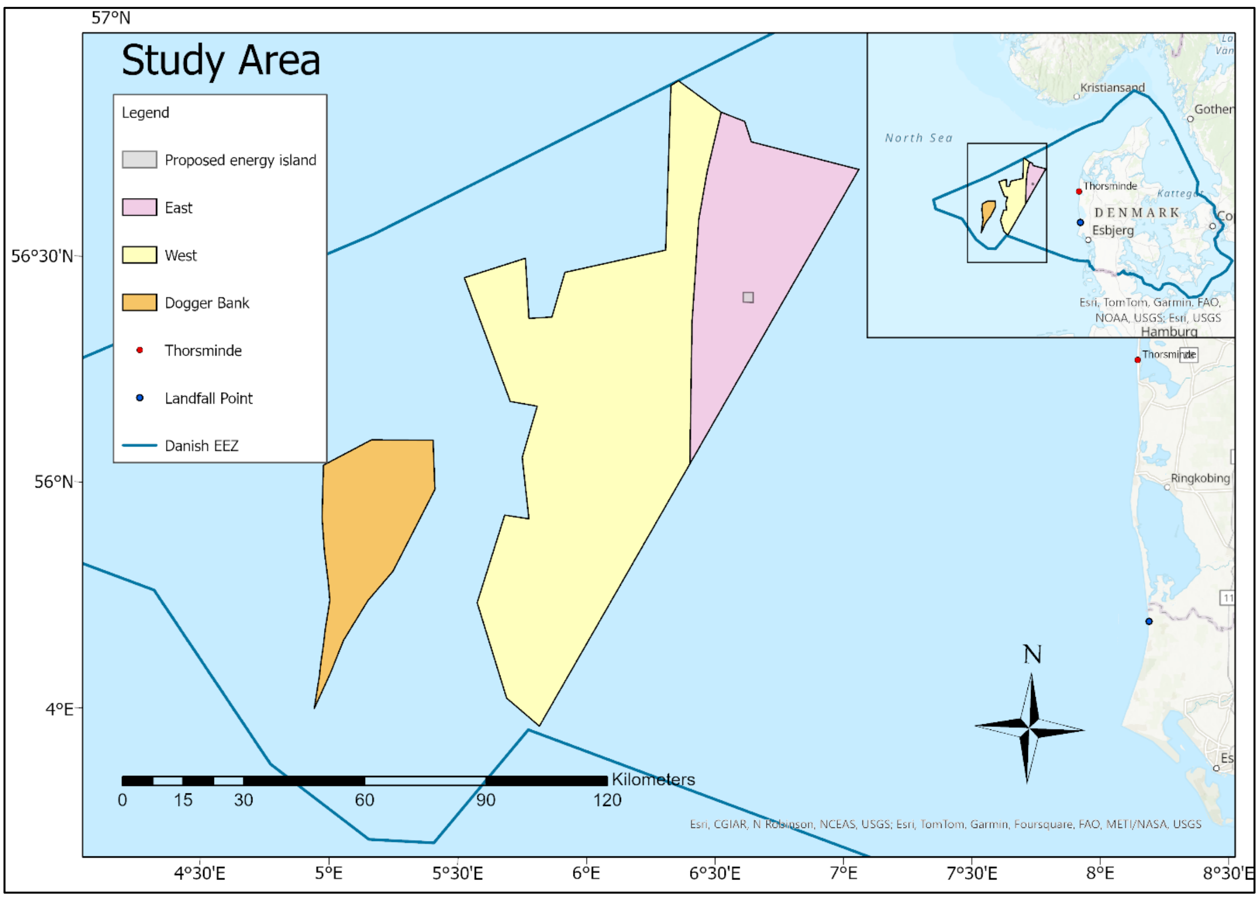

Figure 5. Study area map

[10] Exclusive Economic Zone (EEZ) – an area that can be developed for commercial purposes e.g. mining and energy extraction.

3.1.1 Potential Sites and Justification of the sections

Besides restricting the analysis, the proposed site in the *East* will be tested against the potential sites in the *West* and the *Dogger Bank*. The potential sections are first and foremost chosen due to the proximity of the expected planned energy island i.e. in the same region. The *West* has been reserved for further investigation for future OWFs and an energy island and in the literature, the *Dogger Bank* has been mentioned as another potential site due to shallow waters and no steep flanks which otherwise would be favorable for benthic[11] and fish species (Energinet, 2017).

Secondly, the *West* is the largest of the three potential sections in the North Sea. Being the largest of the sections, it would supposedly have a larger variability of the ecosystem, and for the aim of this study, an area with an ecosystem less sensitive to an energy island. The same applies for the *Dogger Bank* which is even more distant from the coast than the *West,* however it is a smaller area.

3.1.2 Characteristics of The Study Area

The total study area has an extent of 7086 km². The *East* has an area of 1644 km². This section includes the area for an energy island proposed by the government due to a shallow water bank in the center of the section and its distance to shore. The seabed substrates consist of a combination of sand and coarse sand in the middle of the area and mixed sediments in the northern part and less so in the southern part (Fig. 6). The section has a minimum distance to shore of 83 km and a maximum distance of approximately 120 km measured from the town of Thorsminde, Denmark. The proposed energy island is located approximately 100 km away from the shore. The sea depth ranges between a minimum of 25.2m, a maximum of 54.6m and a mean depth of 39.17m (Fig. 7). The *West* has an area of 4485 km². The seabed substrates consist of a combination of sand, fine mud and coarse sand in the middle of the section, muddy sand in the southern part and, to a lesser extent, mixed sediment in the northern part (Fig. 6). The distance to shore is a minimum of 114 km and a maximum of approximately 177 km measured from Thorsminde. The sea depth ranges between a minimum of 28m, a maximum of 64.5m and a mean depth of 45.8m (Fig. 7). As a neighboring area with similar substrates, but slightly deeper depth than the *East*, it is assumed that the sand lance density is less than the planned location and therefore a less impact which relates to the research objective.

The *Dogger Bank* has an area of 957 km². The seabed substrates consist of a combination of sand and coarse sand in the northern part, muddy sand and fine mud in the middle part and sand in the southern part (Fig. 6). The approximate distance to shore with Thorsminde as a reference point is a minimum of 175 km and 221 km as a maximum. The depth varies between a minimum of 32.1m, a maximum of 50.23m and a mean of 41,12 (Fig. 7). As a section with almost similar substrates and depths, but a significantly greater distance from the shore and the planned

[11] Benthic species – invertebrates living on the sea floor such as worms, crabs and bivalves.

location, it is assumed that the sand lance density is less than the planned location and therefore a less impact which relates to the research objective. The characteristics of the study area sections are summed up Table 2 below.

Table 2. Characteristics - study area sections

Section	Area (km^2)	Distance to shore (km)	Depth (m)	Sediments
East	1644	Min. 83 Max. 120	Min. 25.2 Max. 54.6 Mean 39.17	Sand, coarse sand, mixed sediments.
West	4485	Min. 114 Max. 177	Min. 28 Max. 64.5 Mean 45.8	Sand, fine mud, coarse sand, muddy sand.
Dogger Bank	957	Min. 175 Max. 221	Min. 32.1 Max. 50.23 Mean. 41.12	Sand, coarse sand, muddy sand, fine mud.

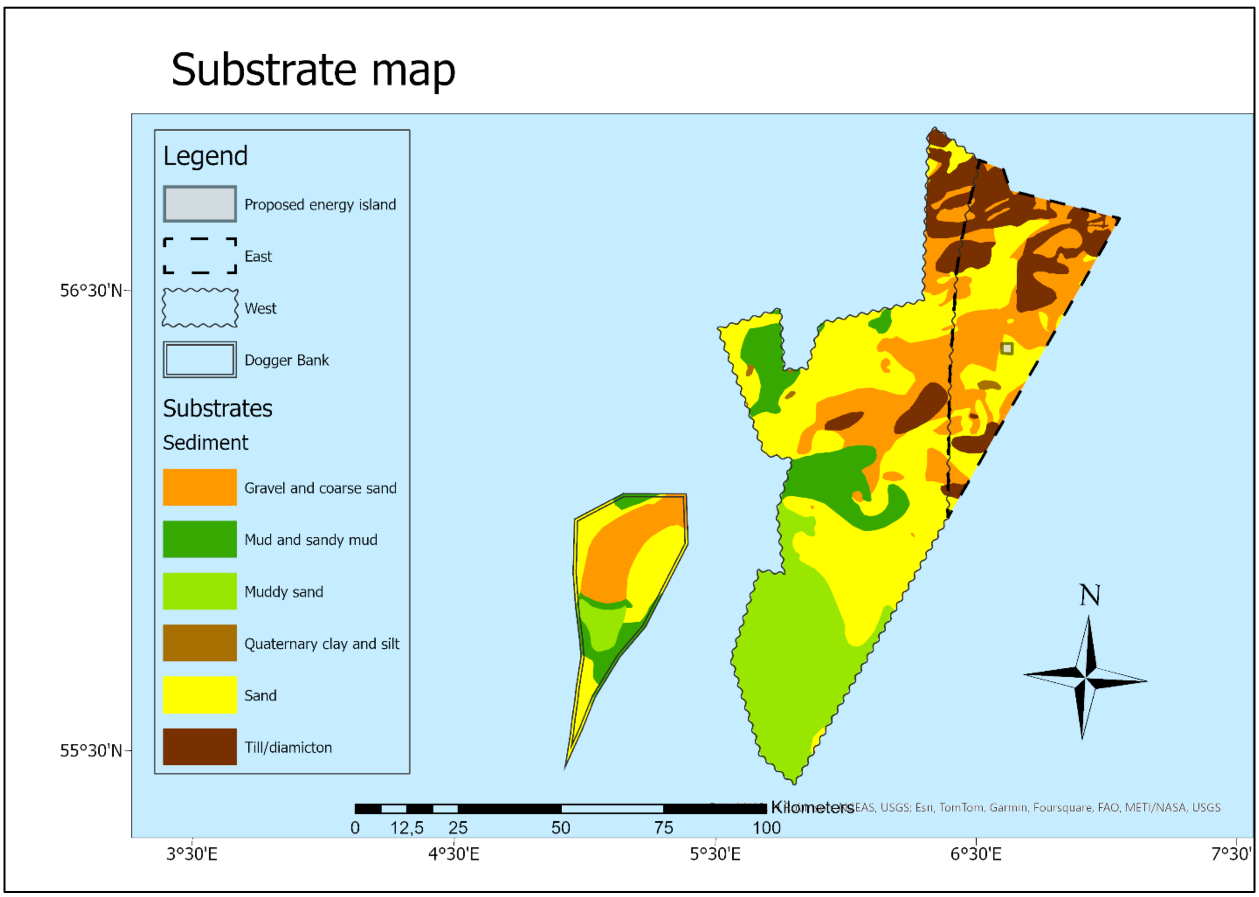

Figure 6. Substrate map (Based on data from EMODnet and Dataforsyningen)

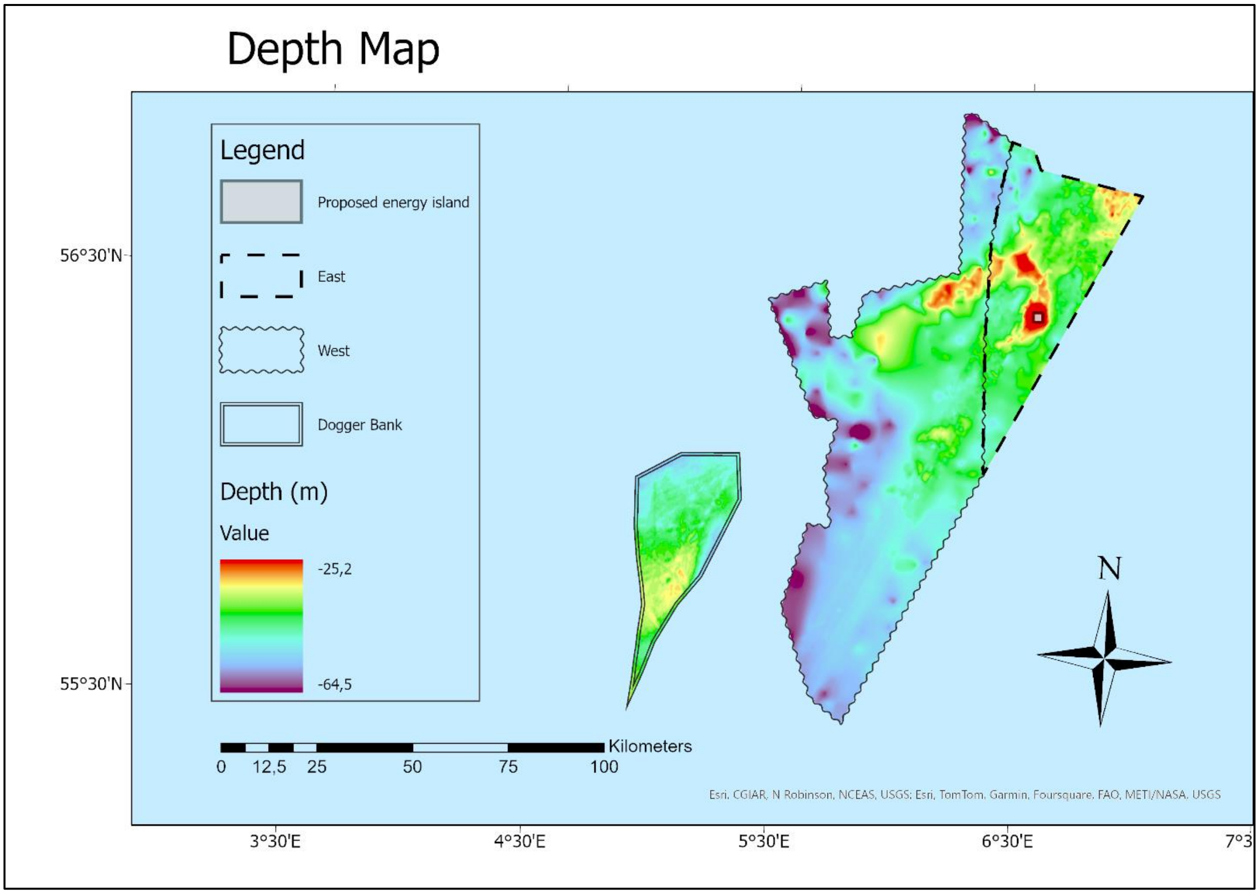

Figure 7. Depth map (Based on data from EMODnet)

The datasets used in this study are obtained to cover biological, physical and human aspects of the study. The datasets are publicly available primarily obtained from the European Marine Observation and Data Network (EMODnet), the Global Wind Atlas website, The Danish Environmental Protection Agency (miljøstyrelsen) and OSPAR Data and Information Management System[12] (Table 3). Some of the sources have been used in a similar assessment such as the screening of OWFs areas in the North Sea (Danish Energy Agency; COWI, 2022). The datasets will function as attributes for this study.

[12] Oslo Paris Convention (OSPAR) - Convention for the Protection of the Marine Environment of the North-East Atlantic.

Table 3. Data sources (vector, raster and numerical data)

Dataset description	Reference
Cables, pipelines and telecommunications	EMODnet, Human activities (2023)
Maritime EEZ boundaries	Marine Regions (2019)
Offshore energy polygons and vessel traffic routes	Dataforsyningen, DEA (2017), EMODnet Human activities (yearly update). Vessel traffic routes are aggregated datasets of annual averages in the periods 2017-2023
Sand lance abundance and distribution	EMODnet, Biology, ICES (2010)
Seabed substrates	Geology, GEUS (2014/2020)
Sea depth	EMODnet, Bathymetry (2022)
Shipwrecks and UXO[13]	ODIMS[14] (2016), Northern Jutland Coast Museum (2021)
Windspeed	Global Wind Atlas (2023)

The dataset for subsea cables and telecommunication and the pipeline data were created by COGEA[15] in 2014 and 2017 respectively for EMODnet and is being updated yearly. The datasets are aggregations of the underlying data sources. This dataset will map existing and planned cables and pipelines and therefore identify unsuitable areas for a potential energy island.

The maritime EEZ boundaries were created by the Flanders Institute for their website marineregions.org and last updated 2019. A subset of this dataset will be used to delineate other datasets in which the study will take place i.e. it will clip the other datasets to the study area so that they do not exceed the Danish EEZ.

The Offshore energy dataset was initially created in 2017 by the Danish Energy Agency (DEA) and has been regularly updated since then. The dataset is used as it consists of the offshore energy areas planned by the government. The datasets will be combined with another dataset of the Dogger Bank digitized by the author i.e. drawn on top of bathymetry data from EMODnet. These datasets will be relevant when comparing the planned location with potential locations within the study area. Existing offshore structure areas are unsuitable areas as they are already occupied.

Furthermore, data created by CETMAR for EMODnet with a yearly update has been obtained. The datasets come as points and polygons and contain attributes such as names, number of

[13] Unexploded Ordnance (UXO) old explosives (munition).
[14] ODIMS - OSPAR Data and Information Management System.
[15] COGEA SRL, Business Management Consultants.

turbines, status (approved, planned, dismantled etc.), country, year, power (MW), area (km^2) and distance to shore.

The sand lance abundance and distribution data were created in 2010 by ICES[16] for EMODnet. The dataset is a gridded data-interpolated variational analysis (DIVA) and based on bottom trawl surveys. The survey data was originally sample points that have been interpolated i.e. have undergone an algorithmic process to approximate the values between the points to create a continuous surface. The units are catch per unit effort (CPUE) which is a log-transformed scale of representing data where the values are scaled according to the logarithm of the actual values. This type of scale is particularly useful when dealing with data that spans a wide range of magnitudes or when you want to emphasize smaller values without ignoring larger ones. In this context, the lesser the sand lance abundance (CPUE) the more suitable area for an energy island. The dataset is an aggregation of the years 1980-2013.

The seabed substrates data are based on seismic surveying in combination with sample tests and interpolated between the data points. It was created by GEUS in 2013 and updated 2020 for EMODNET. It is set in scale 1: 250000. This dataset will identify suitable and less suitable areas to build an energy island. Sandy substrates areas are for instance very suitable areas whereas mixed sediments and muddy substrates are less suitable and non-suitable areas respectively.

Sea depth is a multi-layer digital terrain model (DTM) from EMODnet in gridded form of 1/16 * 1/16 arc minutes (ca. 115-meter grid). The dataset is based on a collection of bathymetric surveys, composite DTMs and satellite bathymetry data. This dataset will identify the areas with suitable and non-suitable areas. The less depth the more suitable area for an energy island.

UXO data was obtained from an ODIMS dataset in February 2016 and has undergone quality control by ODIMS. The shipwreck data was based on coordinates from a report by Jan Hammer Larsen of the Northern Jutland Coast Museum. The report, which is publicly available on DEAs website (Larsen, J.H., 2021) is an archeological analysis about wrecks in the study areas 'East' and 'West'. This dataset will identify less suitable areas for an energy island and point out the risk and a further investigation and a possible clearance of munition and/or shipwrecks.

The windspeed data from the Global Wind Atlas website (GWA v. 3.1) is created in a partnership between the Technical University of Denmark (DTU Wind), The World Bank and the International Finance Corporation (IFC). The dataset indicates the mean wind speed. The higher mean wind speed indicates a better wind resource. The wind speed was registered at 100m above sea level and the higher mean wind speed the more suitable the area is for an energy island as the surrounding OWFs will be depending on the wind resource.

Most datasets are acquired in vector format except data on sea depth, wind speed, sand lance abundance and vessel traffic which are in raster format.

[16] The International Council for the Exploration of the Sea (ICES).

4.Methodology

4.1 Geographical Information System (GIS)

The study was conducted using a geographical information system (GIS) which is a powerful computer system that can store, process, and visualize spatial and numerical data. It can be used when dealing with planning situations and as a spatial support system in complex decision situations with conflicting objectives and criteria. ArcGIS Pro 2.7.3 was used in this study as it is an industry software within the GIS field.

4.2 MCDA Techniques

In addition to GIS, a multicriteria decision analysis (MCDA) was implemented. An MCDA is a collection of techniques that can solve complex decision problems involving conflicting objectives and criteria such as environmental and human activities in combination with GIS. Furthermore, GIS in combination with MCDA are commonly used in suitability analyses for finding the best location in space (Pohekar et al. 2003). MCDAs can further be subdivided into *multiobjective decision making* (MODM) and *multiattribute decision making* (MADM).

To distinguish between MODM and MADM, it is essential to understand the definitions of objectives and attributes. An *objective* is a statement of the desired state of a system under consideration. An example of an objective is for instance *an ecosystem friendly OWF energy generation*. An *attribute* is a property of an element of a real-world geographical system. The property is a measurable quantity or a quality of a geographical entity. Examples of attributes are *depth*, *distance to shore*, *windspeed* etc. The generic term *criterion* covers both the concepts of attribute and objective.

A MODM deals explicitly with the relationship of attributes of alternatives to higher level objectives of the decision maker and this approach involves designing the alternatives and searching for the 'best' decision among an infinite or very large set of feasible alternatives (Malczewski, 1999).

A MADM is used when there is a direct correspondence between attributes and objectives. A MADM requires that choices be made among alternatives described by their attributes. (Malczewski, 1999). A classification of the MCDA methods is shown in Figure 8. The characteristics of MODM and MADM are shown in Table 22 in the Appendix section.

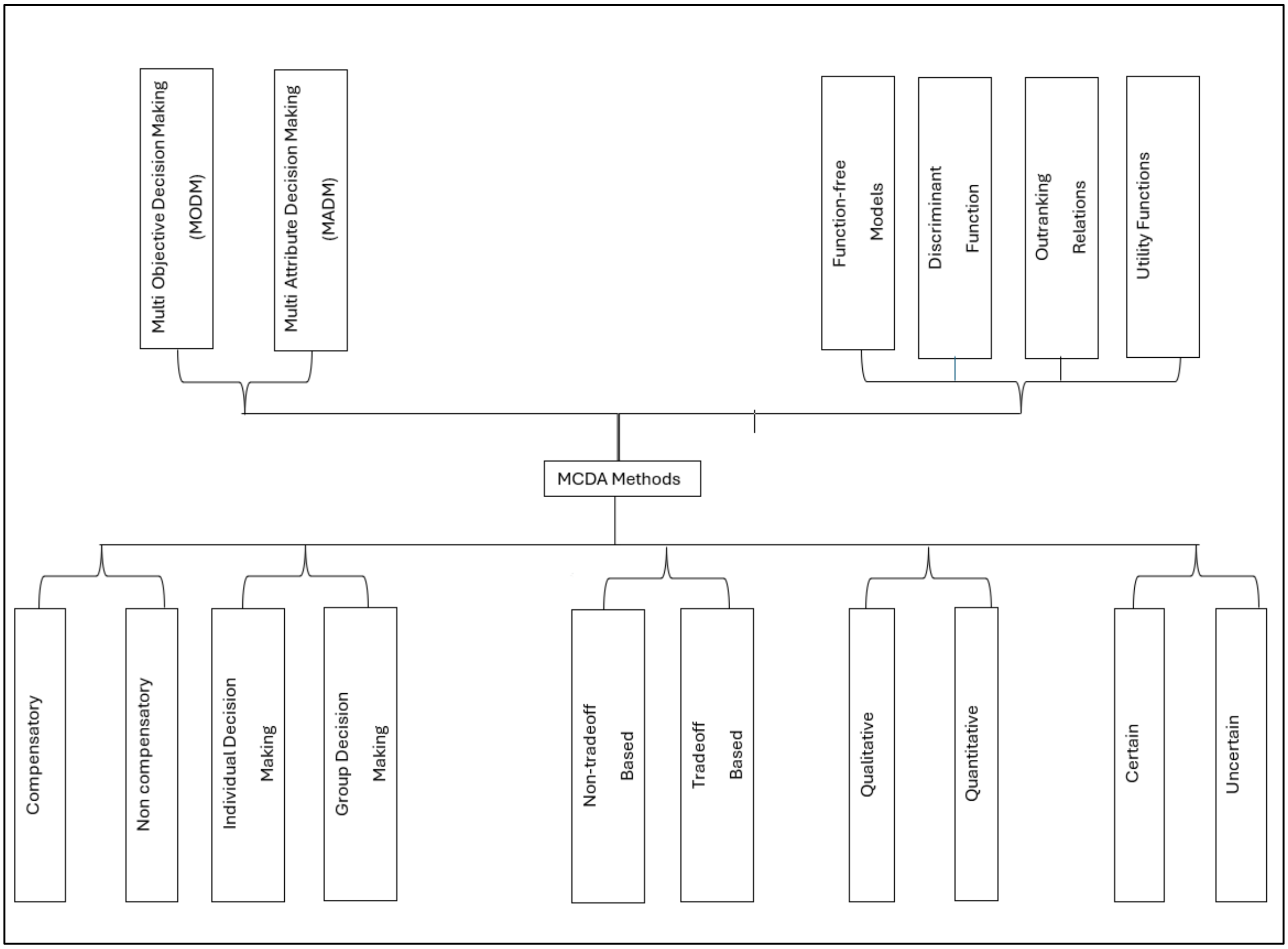

Figure 8. Classification of MCDA methods (Inspired by Taherdoost and Madanchian, 2023)

The MCDA techniques can be *Utility functions* e.g. the Analytical Hierarchy Process (AHP) or the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), *Outranking Relations* e.g. the Elimination and Choice Translating Reality (ELECTRE) or Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE). *Function-free models* refer to methods that do not rely on an explicit utility or value function and often use qualitative data or direct pairwise comparisons without converting them into numerical functions e.g. the Dominance-based Rough Set Approach (DRSA). The *Discriminant Function* methods involve creating a discriminant function to separate alternatives based on their characteristics e.g. the Linear Discriminant Analysis (LDA) (Taheerdoost et al., 2023)

Utility Functions are often based on a pairwise comparison in combination with weights (importance factors) resulting in a prioritized order of feasible decision alternatives with the best alternative ranked highest. *Outranking Relations* are also based on a pairwise comparison between the alternatives and rank the alternatives according to their scores. After eliminating the less favorable alternatives the result is often a decimated group of alternatives and not so much 'the best alternative'. An MCDA method can be *Individual Decision Making* i.e. a single person or *Group Decision Making* with groups of different stakeholders. Furthermore, an MCDA method can have *Certain* or *Uncertain* traits.

The certain combination is an exact method constructed for a condition of assumed certainty. The method assumes that there is only one possible result (which is known) for each alternative course of action (Malczewski, 1999). The uncertain combination is a method that incorporates the concept of uncertainty into multicriteria rules explicitly. The methods use a probability distribution rather than a single number for describing the overall performance (score) of each alternative (Malczewski et al., 2015).

Fuzzy methods are sometimes used in combination with MCDA techniques when dealing with uncertainty (imprecision) by grouping data into classes without crisp boundaries. The classes will thus represent a degree of membership between zero (0) and one (1), where the value zero equals 'not suitable' and the value one equals 'ideal location'. Accordingly, real numbers closer to zero represent less suitable locations and real numbers closer to one represents more suitable locations. These methods are appropriate when describing ambiguity, vagueness and ambivalence.

4.2.1 Analytic Hierarchy Process

The analytic hierarchy process (AHP) in combination with fuzzy methods was the chosen MCDA technique for this study. AHP is a technique developed by T. L. Saaty (Saaty, 1987). It is a structured technique for organizing complex decision problems based on mathematics and psychology. It models the decision problem as a hierarchy of an overall goal, attributes, criteria, and alternatives i.e. different locations in the study area as shown in Fig. 9.

4.2.2 Comparison Matrix and Scale of Importance

Each criterion is compared to one another in a comparison matrix and assigned an integer from 1-9 or the reciprocal value to assess the individual preference between two elements in relation to elements in the next higher level. The integer scale is shown in Table 4. The method then relies on the computation of the eigenvectors of this matrix. These eigenvectors are essentially providing an overall weight of a combination of criteria that is used to emphasize the relative importance of a certain criterion – in this context a so-called factor map. The method was subjected to two different scenarios: *an ecosystem priority* and *an economic priority.* In the *equal weights* scenario the weights were simply assigned the same value.

Table 4. Scale of relative importance (Saaty, 2000)

Intensity of importance on an absolute scale	Definition
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between two adjacent judgements
Reciprocals	if activity *i* has one of the above numbers assigned to it when compared with activity *j*, the *j* has the reciprocal value when compared to *i*.

The choice of the AHP approach was made for several reasons. It is a commonly used approach in complex decision situations with conflicting objectives and criteria and is widely used in the energy sector. Especially within renewable energy planning, energy resource allocation, transportation energy planning and electric utility planning (Pohekar et al., 2004; Bennui, 2007; Al-Yahuai et al., 2012; Sánchez-Lozano et al., 2016; Chaouachi et al., 2017; Bobeck, 2017). Using other MCDAs was beyond the scope of this study.

The approach has an intuitive appeal, a simple decomposition of the decision problem in a hierarchy which makes it applicable for either a single or a group decision making with multiple stakeholders. It is flexible and able to mix both quantitative and qualitative criteria (Pohekar et al., 2004). The latter of which had to be converted to an integer value between 1-9 just as the quantitative criteria to fit into the same framework.

4.2.3 Consistency Ratio

An advantage of the AHP approach is the calculation of the consistency ratio (CR) which determines if the comparisons are made consistent. The consistency ratio can be found by first calculating the consistency vector (CV), next the principal eigenvalue(λ_{max}), then the consistency index (CI) and finally the CI is divided by a random index (RI) adapted from Saaty (1980) (Table 5).

The CR becomes relevant when the comparisons are inconsistent and a re-evaluation of the pairwise comparisons is required.

Table 5. Random inconsistency indices (RI) for n=1,2....,15 (Saaty, 1980)

n	**RI**	***n***	**RI**	***n***	**RI**
1	0.00	6	1.24	11	1.51
2	0.00	7	1.32	12	1.48
3	0.58	8	1.41	13	1.56
4	0.90	9	1.45	14	1.57
5	1.12	10	1.49	15	1.59

The consistency vector (CV) is found by multiplying the assigned weight for the first criterion times the first value of the original pairwise comparison (integer 1-9 or its reciprocal), then multiplying the second weight times the second value, the third criterion weight times the third value etc. and then summing these values across the rows and finally dividing by their respective weight.

The principal eigenvalue(λ_{max}) is calculated by multiplying the column totals in the original comparison matrix by their respective weights and then summed up across the row.

CI is calculated as follows: CI = $\lambda_{max} – n / n – 1$. Calculation of CR: CR = CI / RI.

The calculation of eigenvalue (λ_{max}), CI and CR in this study is described in detail in A8-2 and A8-4 in the Appendix section for the ecological and economic scenarios respectively.

The CR index is important for a decision maker to assure that the judgements are consistent and the final decision is made well. A CR index less than 0.1 is considered acceptable whereas an index greater than 0.1 requires a re-evaluation of the pairwise comparison (Pohekar et al., 2004; Bobeck, 2017). In this study, the judgements in the ratio matrix were done solely by the author’s subjective choice.

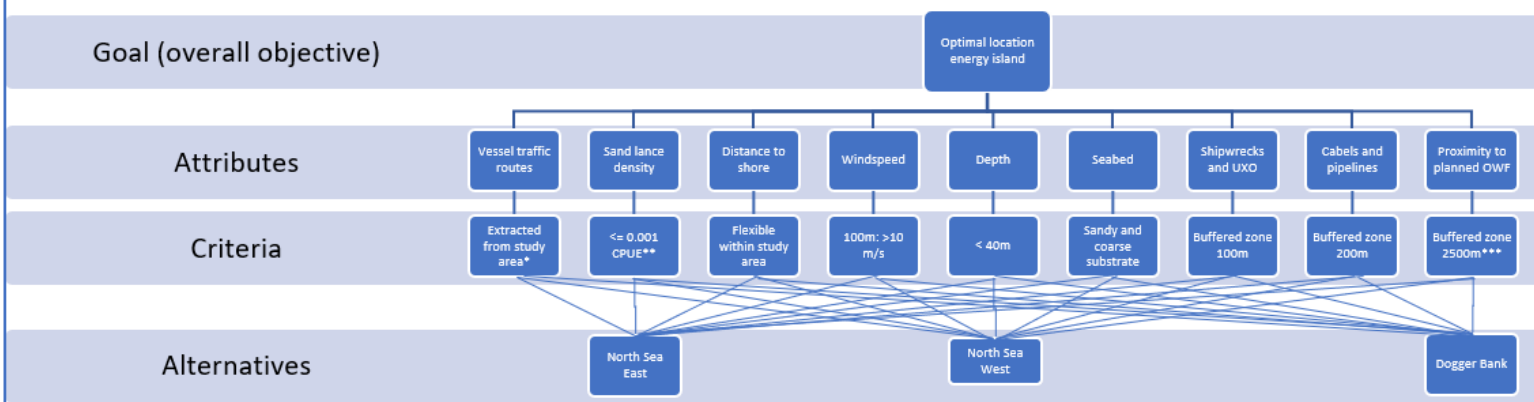

Figure 9. Study modelled in an AHP hierarchy

*Vessel traffic layer was derived from data from EMODnet, Human Activities > Maritime Spatial Planning > MSP Zoning Areas > Maritime Traffic Flows. The layer had already been buffered at the source and was extracted from the study area in the analysis.

**The Catch Per Unit Effort (CPUE) is a log-transformed scale. A threshold at 0.001 CPUE was chosen for the analysis.

***Proximity to a planned OWF was a point feature data from EMODnet, Human Activities > Maritime Spatial Planning. The point data was buffered 2500m using the Euclidean Distance and Reclassify tools to leave enough space for the OWF area and calculating optimal distances (3-6 km) to a potential energy island.

4.3 Analysis Stages

The actual analysis of the study was performed in three stages. The stages and geoprocessing tools are described in detail in “A6: Stages and Geoprocessing Tools” in the Appendix section.

The first stage was collection of data from external data providers. The second stage involved pre-processing of the obtained data so that it could be overlaid and fit to other datasets.
An ArcGIS Pro project was created for each attribute and its underlying criterion in the same spatial reference system i.e. nine projects in total. At this stage, the constraint and factor analyses were also performed. Finally, in the third stage, the map production and assessments took place i.e. the weighting of attributes, generation of result maps, validation of results, performing sensitivity analyses and assessment of the results was made.

4.3.1 Relevant Tools for the Stages

In the second stage, the most relevant tools were Extract by Mask, Clip (vector), Clip Raster, Buffer, Merge, Feature to Raster, Euclidean Distance, Fuzzy Membership and Raster Calculator. In the third stage, the calculation of weights for the three scenarios (an ecological, an economic and an equal weights scenario) was performed in a comparison matrix using MS Excel and MATLAB and PriEst to validate weights and consistency. The Weighted Sum tool was used for overlaying several rasters, multiplying each by their given weight (derived from the AHP comparison matrix) and summing them together to generate suitability index (SI) maps for the three scenarios. Finally, the overall suitability for the three scenarios was found by multiplying the SI maps with the composite constraint raster in the Raster Calculator. Figure 12 is showing the stages in a flow chart.

4.3.2 Constraint Analysis – Boolean logic

Constraints are attribute criteria that can be expressed using a Boolean logic i.e. as either true which is equal to the value one (1) or false which is equal to the value zero (0). In other words, if the criterion equals the value one, the area is deemed suitable and if the criterion equals the value zero it is deemed not suitable and will be excluded from further investigation.
A constraint map is thus a map layer that outputs the value one or zero after a Boolean logic process, and multiplied with other constraint maps in the raster calculator a composite constraint map can be generated where areas with a zero value will be excluded.
In this analysis, seven attributes were treated as constraints: sand lance density, vessel traffic routes, depth, seabed substrates, shipwrecks and UXO, cables and pipelines and planned OWF. The constraints are described in Table 6.

Table 6. Constraint attributes

Constraint	Attribute	Criterion	Priority perspective
C1	Sand lance density	< 0.001 CPUE = 1; > 0.001 CPUE = 0	Ecosystem
C2	Vessel traffic routes	Vessel routes = 0; non-vessel routes = 1	No particular ecosystem or economic priority
C3	Depth	< 40m = 1; > 40m = 0	Ecosystem / Economic
C4	Seabed substrates	Sandy/ coarse substrates = 1; Other = 0	Ecosystem / Economic
C5	Shipwrecks and UXO	Shipwrecks and UXO = 0, Other = 1	No particular ecosystem or economic priority
C6	Cables and pipelines	Cables and pipelines = 0; Other = 1	No particular ecosystem or economic priority
C7	Planned OWF	Planned OWF = 0; Other = 1	Economic

The constraints C2, C5 and C6 had no ecosystem or economic importance in this analysis but were included as exclusion zones.

4.3.3 Factors – Fuzzy Set Theory

Factors are attribute criteria that can be measured in a continuous scale identifying the degree of suitability i.e. the factors can be expressed using a fuzzy set theory (Zadeh, 1965) which means the criteria can be represented by real numbers ranging from 0 to 1 [0,1] using a membership function. A membership function thus calculates the real numbers (fuzzy numbers) ranging from 0 (not satisfied) to 1 (fully satisfied). More specifically, it is a function that represents any element *x* of *X* partially belonging to a subset *A* of *X,* or the grade of *x* in *A* (Malczewski, 1999).

In other words, the degree of membership of an object *z* in a fuzzy subset *A* can be expressed as a membership ranging from the value zero (0) which equals a not suitable location to the value one (1) which equals an ideal location. All real numbers between zero and one are thus being represented on a continuous scale where a value close to zero indicates a less suitable location and a value close to one a more suitable location.

An advantage with the fuzzy set theory is that it provides a framework for dealing with uncertainty by allowing grouping of individuals into classes without sharply defined boundaries

which is appropriate when describing ambiguity, vagueness, and ambivalence (Hansen, 2005; Bobeck, 2017). A fuzzy set process is also referred to as a standardization of factors.
In this study, the fuzzy set method was considered appropriate as the factor criteria were prone to uncertainties and vagueness such as sand lance density, depth and windspeed all of which are dynamic factors with no sharp boundaries.
According to Zadeh (1965) the fuzzy set theory can be defined by the application of a membership function (MF). There are several types of membership functions to describe fuzzy sets, however, a linear membership function was found appropriate for this study as the relationship between the variables in the attribute criteria were assumed linear.
Other non-linear membership functions such as the logistic sigmoidal (s-shaped) or the exponential (j-shaped) function were found to be less appropriate in this study as it would be difficult to determine non-linearity in this spatial context. Furthermore, a linear membership function has also been used in similar studies (Hansen, 2005; Latinopoulos et al., 2015).
Attribute criteria can either be constraints or factors or both. Five criteria out of the nine attributes in this study were treated as factors as they are considered continuous data without sharp boundaries. The factor attributes were sand lance density, windspeed, depth, distance to shore and proximity to a planned OWF. When performing a factor analysis based on a fuzzy set theory, factor maps can be generated.

4.3.4 Membership Functions – IFMF and DFMF

Two types of linear functions were relevant in this study: the increasing fuzzy membership function (IFMF) (Fig. 10) and the decreasing fuzzy membership function (DFMF) (Fig. 11).
In the IFMF, a high *z* value in a certain subset *A* is more suitable than lower values of *z*. Conversely, in a DFMF a high *z* value in a certain subset *A* is less suitable than lower values of *z*.
Both membership functions have two threshold values 'p' and 'q'. The 'p' value indicates where the value of *z* is fully satisfied and has a membership value equal to one (1). The 'q' value indicates where the value of *z* is least suitable and has a membership value equal to zero (0). The 'p' and 'q' values thus function as thresholds and all real numbers in between them become fuzzy numbers on a continuous scale with degrees from less suitable to very suitable. In the IFMF, the p value is obtained by finding the maximum value of the map layer and the q value is obtained by finding the minimum value of the map layer. In the case of the windspeed factor in this study, the p value is thus 10.44 m/s and the q value is 10.10. Conversely, in the DFMF, the p value is obtained by finding the minimum value of the map layer and the q value is obtained by finding the maximum of the same map layer. In the case of the depth factor, the p value is 25.2m and the q value is 40m.
For instance, an area with higher windspeed is more suitable for an energy island due to complementary OWF's need for the wind resource (IFMF) whereas higher sand lance density is

less suitable in an ecological point of view (DFMF). Similarly, increasing depth is less suitable for an energy island (DFMF). A table of the factor attributes and their related membership function is shown in Table 7. The mathematical expressions for the IFMF and DFMF are shown below in Equations 1 and 2.

$$IFMF\ (z_i) = \begin{cases} 0 & \text{for } z_i < q_i \\ \dfrac{z_i - q_i}{p_i - q_i} & \text{for } p_i \leq z_i \leq q_i \\ 1 & \text{for } z_i > p_i \end{cases} \qquad \text{Eq. 1}$$

$$DFMF\ (z_i) = \begin{cases} 1 & \text{for } z_i < q_i \\ \dfrac{z_i - q_i}{p_i - q_i} & \text{for } p_i \leq z_i \leq q_i \\ 0 & \text{for } z_i > p_i \end{cases} \qquad \text{Eq. 2}$$

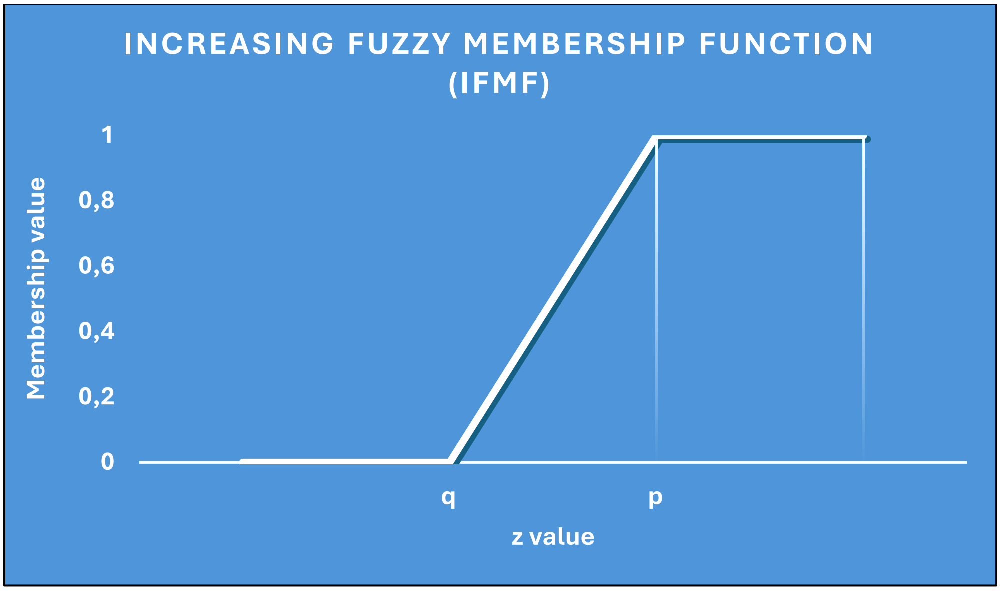

Figure 10. Increasing fuzzy membership function (IFMF) (Inspired by Bobeck, 2017)

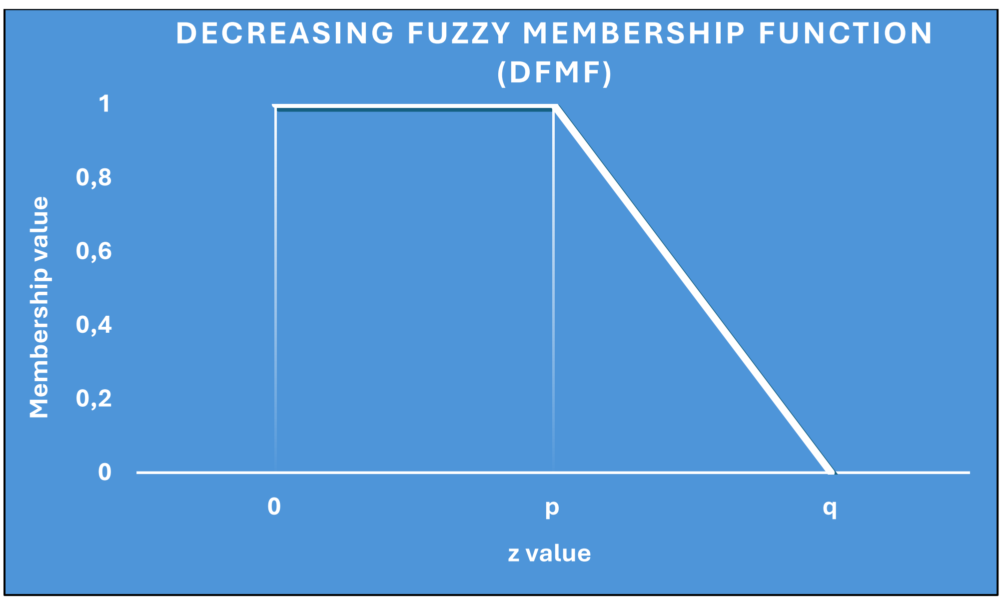

Figure 11. Decreasing fuzzy membership function (DFMF) (Inspired by Bobeck, 2017)

Table 7. Factor attributes

Factor	Attribute	Unit	Membership function (MF)	Priority perspective
F1	Sand lance	CPUE	DFMF	Ecosystem
F2	Windspeed 100m	m/s	IFMF	Economic
F3	Depth	m	DFMF	Ecosystem / Economic
F4	Distance to shore	km	DFMF	Economic
F5	Proximity to planned OWF	km	DFMF	Economic

4.3.5 Decision Rule

Decision rules are methods that can assess a set of evaluation criteria such as constraint and factor maps. There are different decision rules and one of them is the weighted linear combination (WLC) which is commonly used within GIS-based MCDA.

In short, a WLC is a method that combines the maps, and each factor attribute (standardized factor) is multiplied by a weight and the results are summed to produce a composite map (Malczewski et al., 2015). The choice of WLC was considered appropriate as it has been applied in similar studies (Hansen, 2005; Latinopoulos et al., 2015; Bobeck, 2017) often in combination with both GIS and AHP. Another advantage with the WLC method is that it outputs resulting cell values in the same range as those in the factor maps i.e. between zero and one.

4.3.6 Suitability Index

By using the WLC process, a suitability index (SI) can be generated. An SI map is a compilation of all factor map layers of which each raster cell denotes a degree of suitability for an optimal location of an energy island. The equation of the suitability index is shown in Equation 3 below:

$$SI_j = \sum_{i=1}^{n} w_i x_{i,j} \qquad \text{Eq. 3}$$

Where *SI* is the suitability index score for cell *j*, w_i is the weight for factor *i* (*i* = 1, …….5) and $x_{i,j}$ is the standardized fuzzy membership value of cell *j* for factor *i.*

4.3.7 Reclassified SI and Overall Suitability Maps

Following the generation of suitability index maps, a reclassification of the maps was performed i.e. the maps were grouped into three classes: 'Low Suitability', 'Medium Suitability' and 'High Suitability' to give a better overview of the suitability of the study area in the three scenarios. Lastly, the composite constraint map was factored into the three suitability index maps to obtain the resulting maps identifying an optimal location in the three different scenarios. Hence, the overall suitability maps would reflect areas ranging from 'Not Suitable' to 'High Suitability' (Table 8).

Table 8. Suitability class index

Suitability Class	Description
0: Not Suitable	SI = 0
1: Low Suitability	0 < SI ≤ 0.5
2: Medium Suitability	0.5 < SI ≤ 0.75
3: High Suitability	0.75 < SI ≤ 1

4.3.8 Sensitivity Analysis and Study Workflow

Before the actual conclusion of the results and addressing of the research questions, a sensitivity analysis i.e. a slight change of the weights was performed to determine the robustness of the analysis.

In summary, the study was using GIS computer software in combination with AHP which is a multicriteria decision analysis approach and WLC as a decision rule. This configuration has been widely used in site selection analyses. It was found appropriate for this study due to earlier experience in the offshore industry with complex decision situations.

Furthermore, the AHP approach was chosen as it is a simple, intuitive modelling of the objective, criteria and alternatives which could be a strength when dealing with multiple decision makers with different preferences and knowledge backgrounds.

Also, it related well to the research questions in this study as the AHP allowed flexibility by including or excluding further criteria or objectives when deemed necessary (Chaouchi et al., 2017). This flexibility would also be useful in the present study when using other attributes such as sand fluctuation, hydro dynamics etc. which could simply be added, and existing attributes could be excluded if necessary. However, these considerations were beyond the scope of this study.

Finally, the AHP provided a clear and complete ranking of the alternatives compared to the outranking methods which can be rather nontransparent for decision makers due to complex calculations plus they only output a partial ranking of incomparable alternatives (in the case of multiple alternatives) which may require further analysis and judgement. A general workflow of the above is shown in Figure 12.

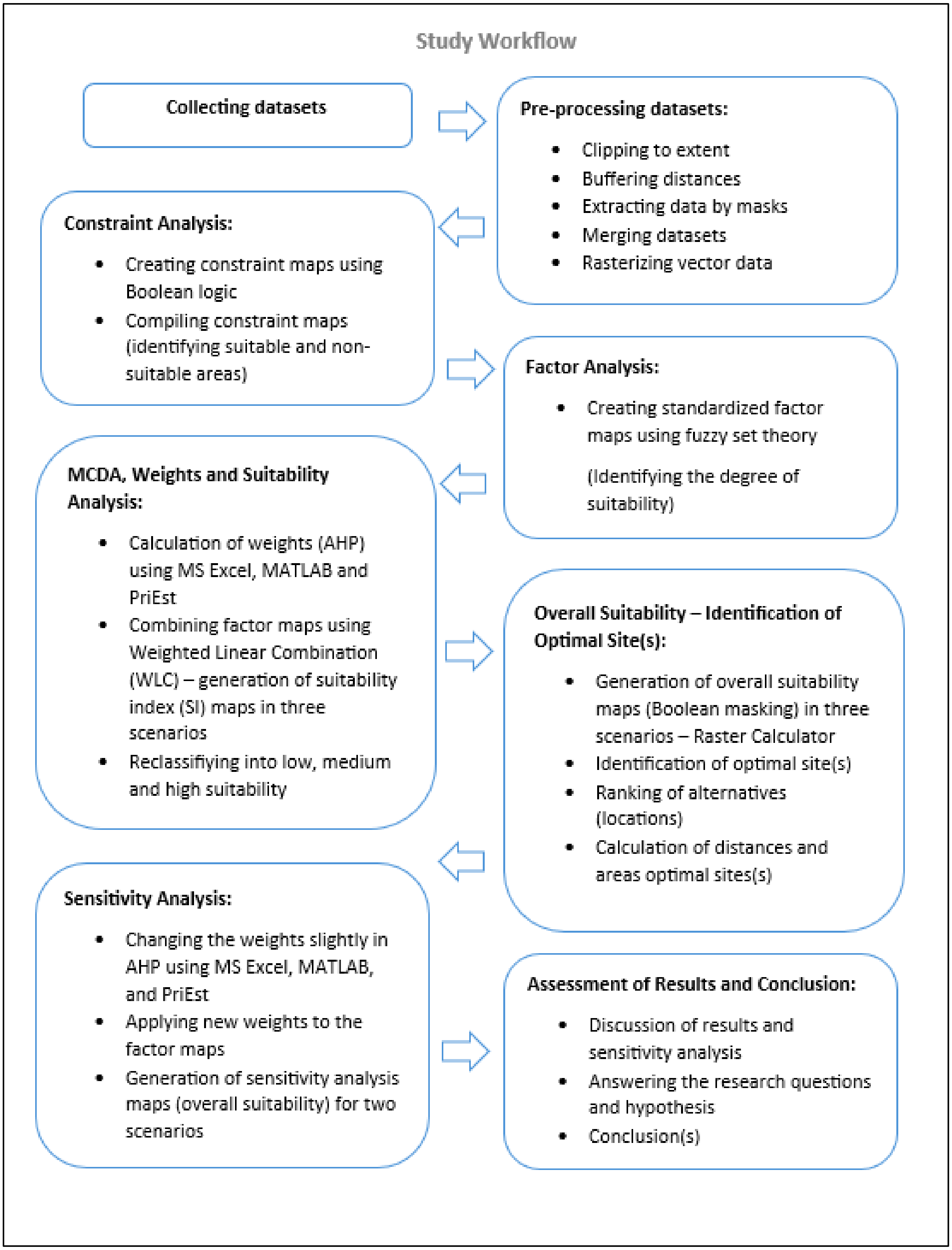

Figure 12. Study workflow

5. Results

5. 1 Intermediate Results

Table 9. Results from pre-processing stage

Attributes	Values and categorical data		
	North Sea East	**North Sea West**	**Dogger Bank**
Sand lance density (CPUE)	Min. – 0.000318 Max. 0.000619	Min. – 0.003965 Max. 0.008605	Min. 0.01197 Max. 0.095214
Windspeed at 100m height (m/s)	Min. 10.24 Max. 10.44 Mean. 10.37	Min. 10.13 Max. 10.44 Mean. 10.26	Min. 10.10 Max. 10.21 Mean. 10.17
Vessel traffic routes - buffered 100m (km²)	0	802.4	190.8
Depth (m)	Min. 25.2 Max. 54.6 Mean. 39.17	Min. 28 Max. 64.5 Mean. 45.8	Min. 32.1 Max. 50.23 Mean. 41.12
Seabed substrates	Sand, coarse sand and mixed sediments.	Sand, coarse sand, mixed sediments, muddy sand, and fine mud.	Sand, coarse sand, mixed sediments, muddy sand, and fine mud.
Shipwrecks and UXO (points) – buffered 100 m (km²)	3 recent shipwrecks 1 sunk coaster 1988 1 unknown wooden vessel 1 unknown iron vessel 1 British WW2 submarine Total buffered area: 0.22	1 shipwreck 0.03	None 0
Distance to shore -landfall point (km)	Min. 118 Max. 164.6 Mean. 135.4	Min. 120.2 Max. 189.6 Mean. 150.2	Min. 179.9 Max. 208 Mean. 195.1
Cables and pipelines			

(buffered 200m) km²	14.70	149.17	20.42
Planned OWFs – buffered (km²)	None	None	1 (Vikinge Banke) 96.90

The result after the pre-processing stage is shown in Table 9 above. Several attributes were remarkable and worth mentioning. According to the sand lance density (CPUE) only the Dogger Bank had a positive minimum value i.e. 0.01197 whereas the East and West showed minimum values of -0.000318 and -0.003965 respectively. Furthermore, the Dogger Bank had a significantly higher maximum value of 0.095214 compared to the East and West with values of 0.000619 and 0.008605 respectively.

The windspeed (m/s) attribute had a range between a minimum of 10.10 m/s and a maximum of 10.44 m/s for the whole study area. However, the East has the highest mean windspeed at 10.37 m/s.

The vessel traffic attribute was calculated in square kilometers. The East had no vessel traffic routes in its section. An actual vessel traffic route went along its eastern boundary but did not cross the section. More remarkably, the West had an area of 802.4 km² and the Dogger Bank had an area of 190.8 km² of vessel traffic routes.

The depth (m) attribute was ranging from a maximum 64.5m in the West to a minimum of 25.2m in the East. The East section also had the lowest mean of 39.17m compared to 45.8m and 41.12m in the West and Dogger Bank respectively.

The shipwrecks and UXO objects were buffered 100m which was considered appropriate in this context and used in the COWI fine screening (2022) and were calculated in square kilometers. There were no detected objects in the Dogger Bank, one detected shipwreck in the West at 0.03 km² and seven shipwrecks in the East section at a total of 0.22 km².

The distance to shore attribute was calculated in kilometers from the landfall point and had a minimum of 118 km to the nearest point in the East and a maximum of 208 km to the farthest point in the Dogger Bank.

The cables and pipelines objects were buffered 200m which was considered reasonable to give enough space away from a potential energy island. The same buffer distance was used by COWI (2022) in its fine screening. The buffered areas were calculated in square kilometers. The West showed a significant 149.17 km² compared to a mere 14.70 km² and 20.42 m² for the East and the Dogger Bank respectively.

Finally, the planned OWF close to the Dogger Bank was buffered 2500m as a potential energy island is supposed to be minimum 2.5 km away from the surrounding OWFs according to DEA (Energistyrelsen, 2023) and was calculated to have an extent of 98 km² of the Dogger Bank section. There were no planned OWFs in the East and the West sections.

5.2 Constraint Analysis and Constraint Maps

Based on the constraint analysis mentioned in the Methodology section (Table 6) above, seven individual constraint maps were generated. All separate constraint maps are shown in "A7: Individual Constraint Maps" in the Appendix section. After this analysis, the exclusion zones for each attribute were determined. A summary of the exclusion zones for each attribute and the overall composite constraint map is shown in Table 10 below.

- **Sand Lance Constraint (C1)**

In the sand lance constraint map (Fig. 28), the suitable areas for a potential energy island were reclassified to the value 1 and the unsuitable areas were reclassified to the value 0. The unsuitable areas were identified in the southern area of the West section and all the Dogger Bank due to a sand lance density higher than 0.001 CPUE.
The total amount of cells in the study area: 710 426. The amount of cell with zero value: 143 938.
The exclusion zones in percent of total study area: 143 938 / 710 426 = 0.2026.
The unsuitable exclusion zones were about 20% corresponding to an area at about 1417 km².

- **Vessel Traffic Constraint (C2)**

The vessel traffic constraint map (Fig. 29) showed unsuitable areas across the southwestern part of the West and across the central Dogger Bank and the southernmost tip. There was no vessel traffic routes in the East.
The total number of cells in the study area: 708 326. The number of cells with a zero value: 99 116. Exclusion zones in percent of total study area: 99 116 / 708 326 = 0.1399. The unsuitable exclusion zones were about 14% corresponding to an area at about 992 km².

- **Depth Constraint (C3)**

In the depth constraint map (Fig. 30), the suitable areas with a depth < 40m were mainly identified in the northern part of the East and the West and in the central and southern part of Dogger Bank. The total number of cells in the study area: 708 409. The number of cells with a zero value: 523 840. The exclusion zones in percent of total study area: 523 840 / 708 409 = 0.7394. The unsuitable exclusion zones were about 74% corresponding to an area at about 5244 km².

- **Seabed Constraint (C4)**

In the seabed constraint map (Fig. 31), the substrates *gravel*, *coarse sand*, and *till* were reclassified to the value 1 or suitable areas as the substrates were considered suitable for any

kind of an energy islands and surrounding OWF structures due to the sand compaction and stability whereas *quaternary clay* and *silt* were reclassified to the value 0 or unsuitable areas as the substrates were considered more volatile and unstable for such structures.
The total number of cells in the study area: 708 321. The number of cells with a zero value: 204 974. The exclusion zones in percent of total study area: 204 974 / 708 321 = 0.2893. The unsuitable exclusion zones were about 29% corresponding to an area at about 2055 km².

- **Shipwrecks and UXO Constraint (C5)**

The shipwrecks and UXO constraint map (Fig. 32) was scaled up to visualize the wrecks and UXO. The wreck and UXO locations were reclassified to the value 0 or unsuitable and the remaining study area reclassified to the value 1 or suitable.
The total number of cells in the study area: 708 321. The number of cells with the value zero: 29. The exclusion zone in percent of total study area: 29 / 708 321 = 4,094188934e-5.
The exclusion zones were very insignificant and therefore set to 0%, however, the spatial extent was calculated to 0.25 km² in absolute numbers.

- **Cables and Pipelines Constraint (C6)**

In the cables and pipelines constraint map (Fig. 33), the cable and pipeline areas were reclassified to the value 0 or unsuitable. The remaining parts were reclassified to the value 1 or suitable. The total number of cells in the study area: 708 321. The number of cells with a zero value: 18 471. The exclusion zones in percent of total study area: 18 471 / 708 321 = 0.026. The unsuitable exclusion zones were 2.6% corresponding to an area at about 184 km².

- **Planned OWF Constraint (C7)**

There were no existing OWFs in the study area, but a planned Viking Banke OWF on the very border of the Dogger Bank. The Planned OWF constraint map (Fig. 34) was scaled up to visualize the buffered area around the planned OWF reclassified as the value zero.
The total number of cells in the study area: 708 315. The number of cells with a zero value: 9 786. The exclusion zone in percent of total study area: 9 786 / 708 315 = 0.01381. The exclusion was about 1.4% corresponding to an area at about 99 km².

- **Composite Constraint Map**

The resulting composite constraint map was generated by multiplying all the individual constraint maps above in the raster calculator. The composite constraint map is shown in Figure 13.

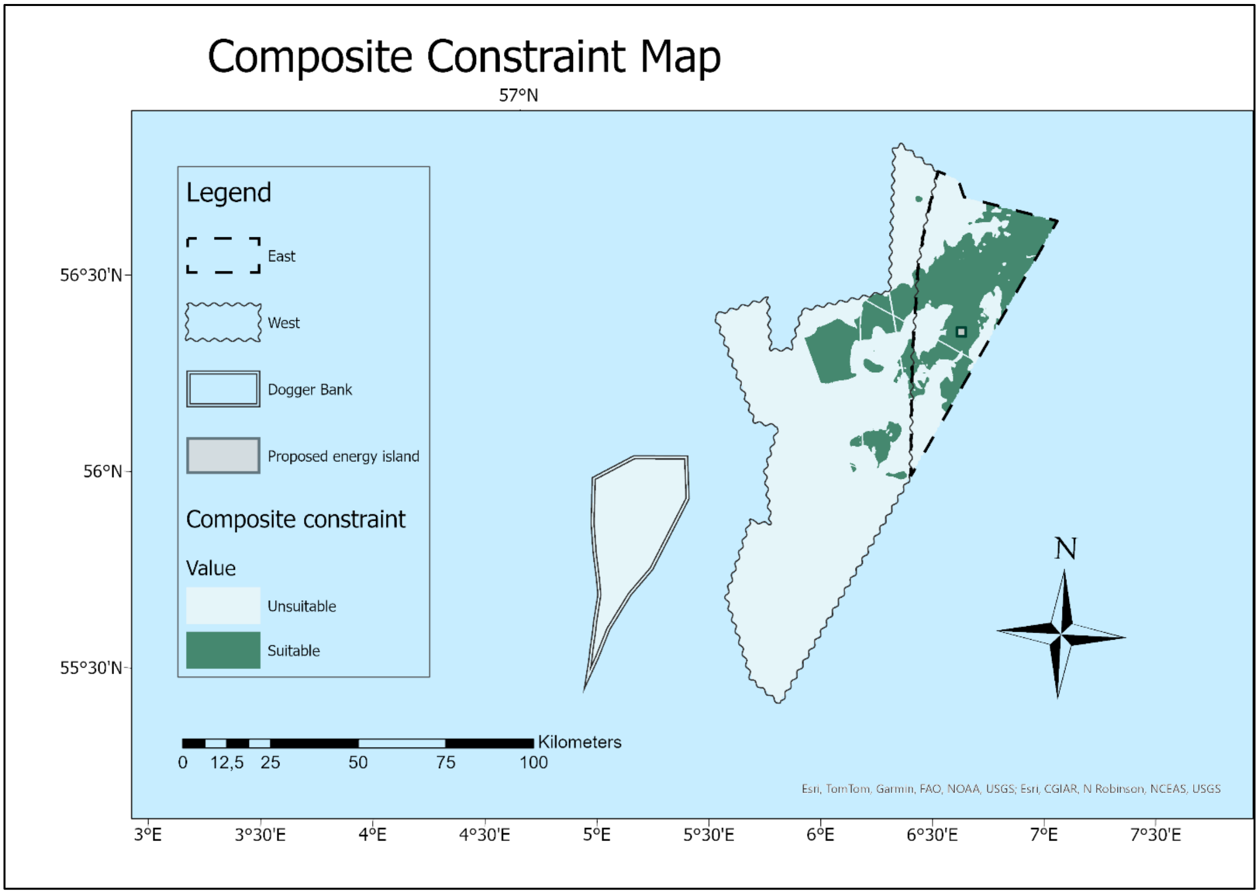

Figure 13. Composite constraint map

The total number of cells in the study area: 700 957. The number of cells with a zero value: 561 675.

The exclusion zone in percent of total study area: 561 675 / 700 957 = 0.8013. The exclusion zone or the unsuitable area was about 80% corresponding to an area at about 5669 km².

As can be seen in the composite constraint map, the suitable area was remarkably reduced and was represented in a green color. The unsuitable area was represented in a white color. Most of the East was feasible for further investigation whereas only the northeastern part of the West was feasible for further investigation. The entire Dogger Bank area was infeasible for further investigation.

Table 10. Area (km²) excluded from study area based on constraint analysis (summary)

Constraint	**Percent of total study area**	**Approximate area of exclusion (km²)**
C1 – Sand lance density	20%	7086 km² * 0.20 = **1417.20 km²**
C2 – Vessel traffic routes	14%	7086 km² * 0.14 = **992.04 km²**
C3 – Depth	74%	7086 km² * 0.74 = **5243.64 km²**
C4 – Seabed substrates	29%	7086 km² * 0.29 = **2054.94 km²**
C5 – Shipwrecks and UXO	0%	**0.3 km²**
C6 – Cables and pipelines	2.6%	7086 km² * 0.026 = **184.24 km²**
C7 – Planned OWF	1.4%	7086 km² * 0.014 = **99.20 km²**
Composite constraint	80%	7086 km² * 0.80 = **5668.8 km²**

5.3 Factor Analysis, Fuzzy Membership and Generation of Factor Maps

In the factor analysis, each of the five separate factor attributes mentioned in the Methodology section (Table 7) were fuzzified (standardized) to a value between zero and one using the Fuzzy Membership Tool. The mean fuzzy membership value which was calculated during the tool operation is the average fuzzy value across the cells in the whole study area for each factor attribute. The mean fuzzy membership value gives a rough idea about the suitability for the individual factor attribute. The mean fuzzy membership values for all factor maps are summarized in Table 11.

5.3.1 Sand Lance Factor (F1)

The sand lance factor map (Fig. 14) showed a significant low fuzzy number (zero or close to zero) in the Dogger Bank due to a high sand lance density indicating a very low or no suitability for an energy island. Conversely, the West and especially the East showed a fuzzy number close to one indicating a medium to high suitability for an energy island. The mean fuzzy membership value, which is the average fuzzy value for the whole study area was measured to 0.9018 indicating a relatively high degree of suitability for this attribute or map layer.

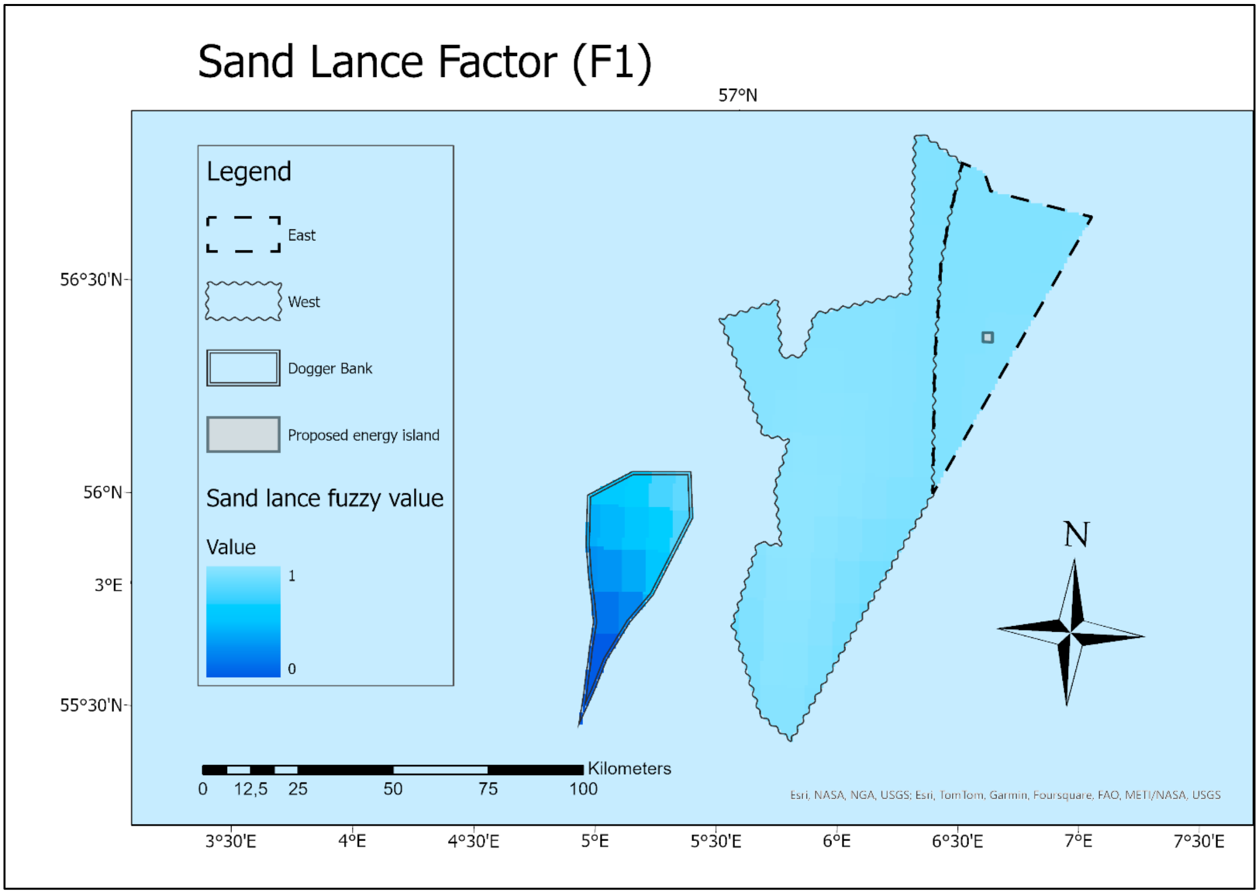

Figure 14. Sand lance factor map

5.3.2 Windspeed Factor (F2)

The windspeed factor map (Fig. 15) showed fuzzy numbers close to one (suitable areas) in the northernmost parts of both the East and the West whereas the southernmost parts of the East and the West and a major part of the Dogger Bank showed fuzzy numbers closer to zero indicating low or no suitability**.** The mean fuzzy membership value for the whole study area was measured to 0.5028 indicating a medium degree of suitability for an energy island for this attribute. The minimum value was calculated to be very close to zero.

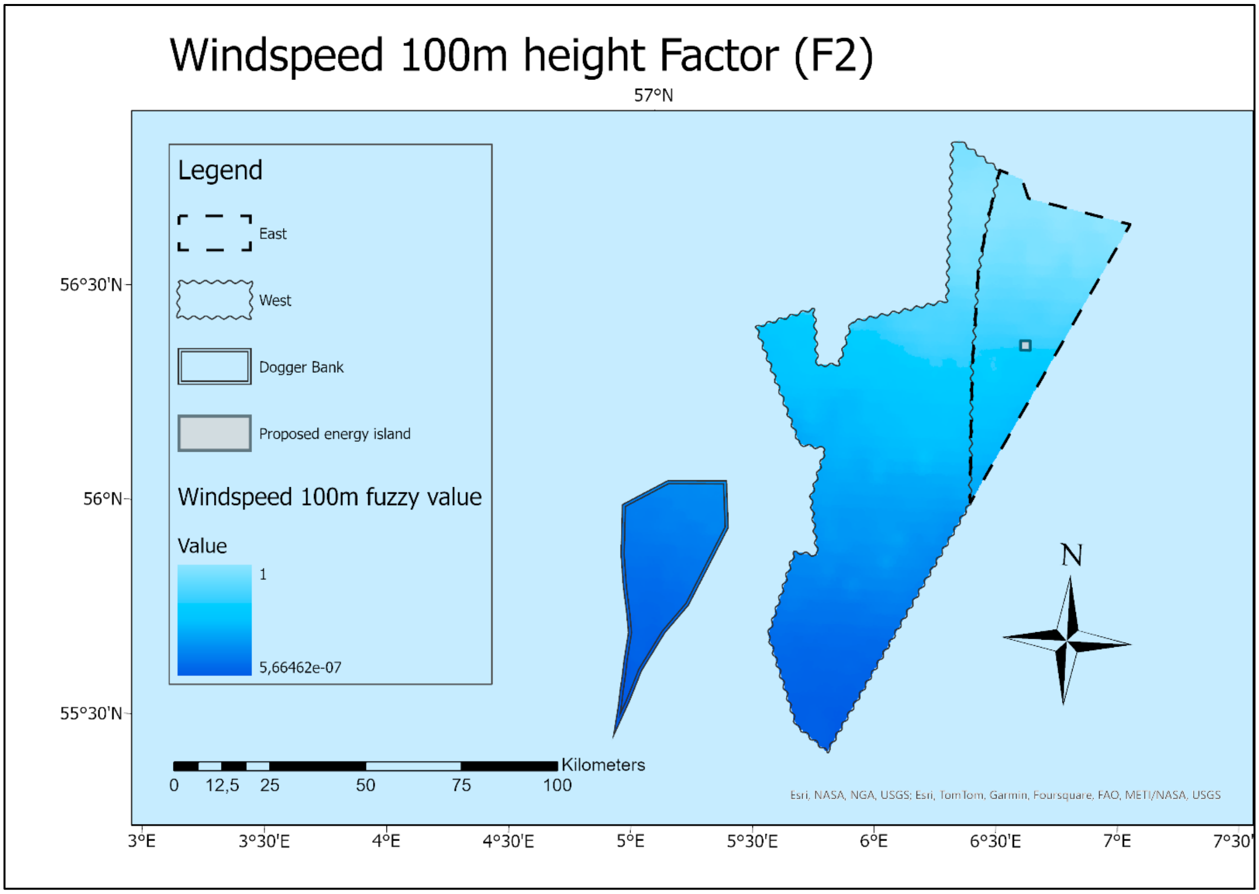

Figure 15. Windspeed factor map

5.3.3 Depth Factor (F3)

In the depth factor map (Fig. 16) the fuzzy numbers close to one and the highest suitability was identified in the northern parts of the East and the West and in the central part of the Dogger Bank. The remaining part of the study area had fuzzy numbers close to zero or zero itself and was therefore considered unsuitable due to lower depth. The mean fuzzy membership value was measured to 0.5310 indicating a medium suitability for this attribute.

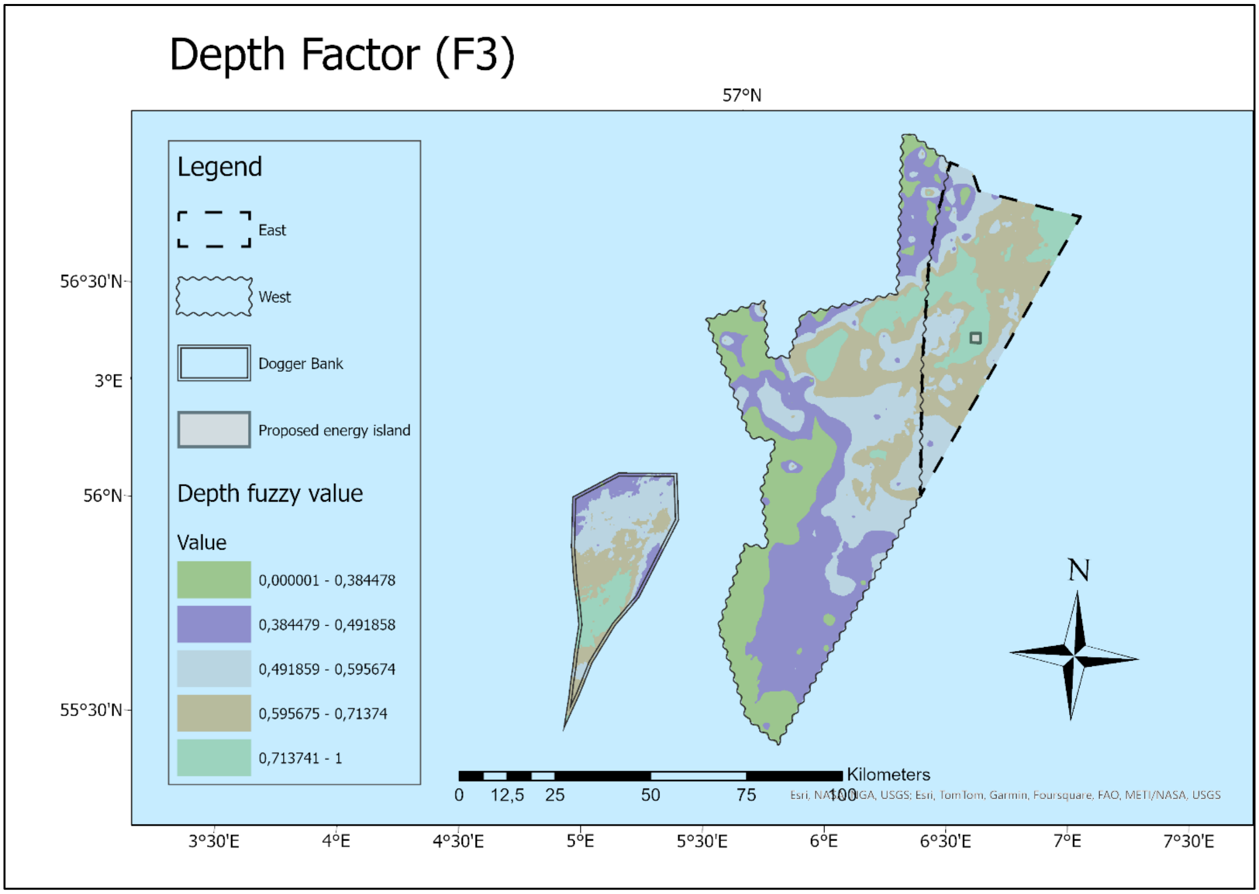

Figure 16. Depth factor map

5.3.4 Distance to Shore Factor (F4)

The distance to shore factor map (Fig. 17) was calculated from the Landfall Point on the Danish west coast. The areas closer to this point, such as the East, had a higher fuzzy number closer to one indicating a higher suitability compared to areas further away such as the Dogger Bank in an economic perspective. In other words, the fuzzy number decreased away from the Landfall Point. The mean fuzzy membership value for this map layer was measured to 0.6129 which is considered a medium suitability for this attribute.

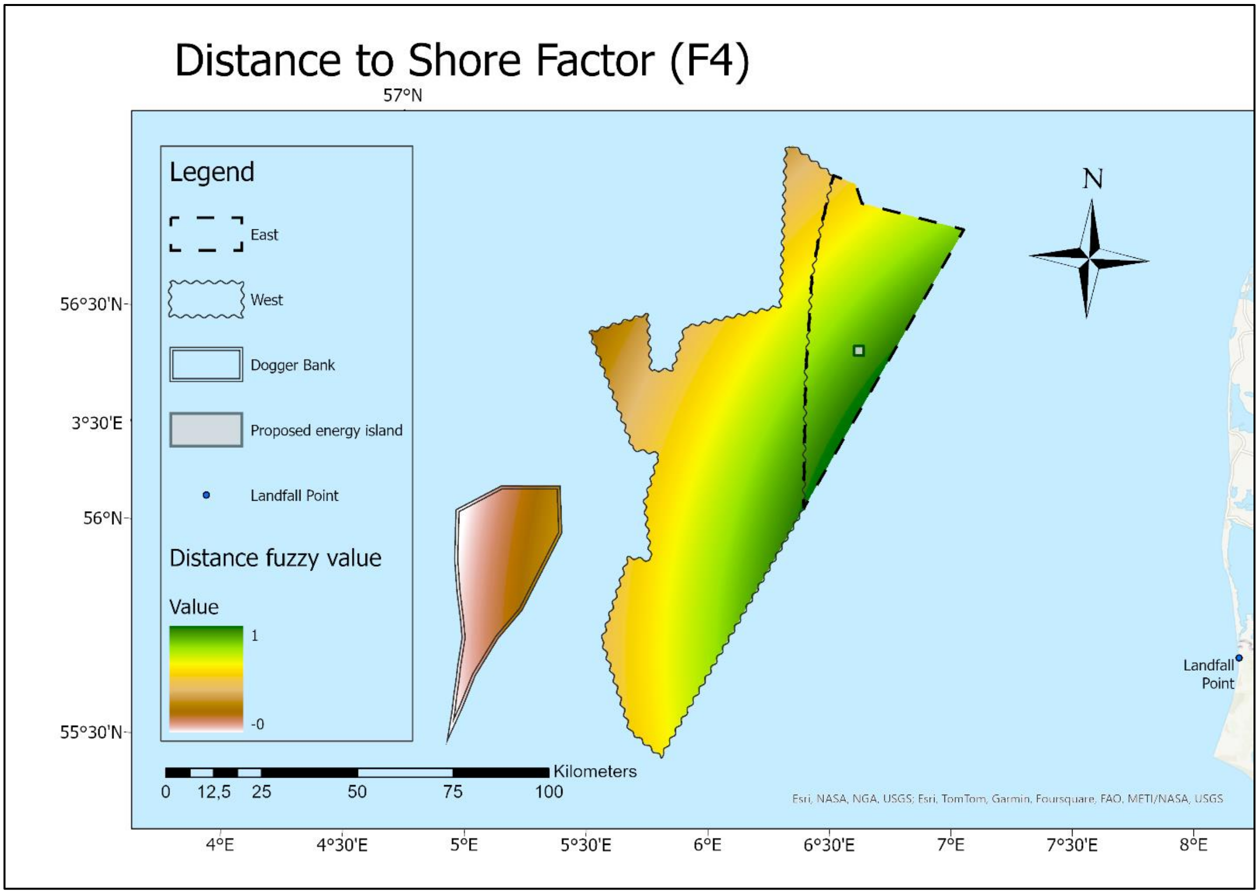

Figure 17. DIstance to shore factor map

5.3.5 Proximity to Planned OWF Factor (F5)

In the proximity to planned OWF factor map (Fig. 18), the area around the planned OWF (Vikinge Banke) was buffered 8960m and assigned a value of zero (unsuitable) whereas the area right outside the buffered zone in the Dogger Bank section had a value of one indicating a high suitability in an economic perspective. The fuzzy number decreased further away from the planned OWF, especially towards the east of the study area indicating a lesser suitability due to increasing cable costs. The mean fuzzy membership value was measured to 0.5472 which is considered a medium suitability for this attribute.

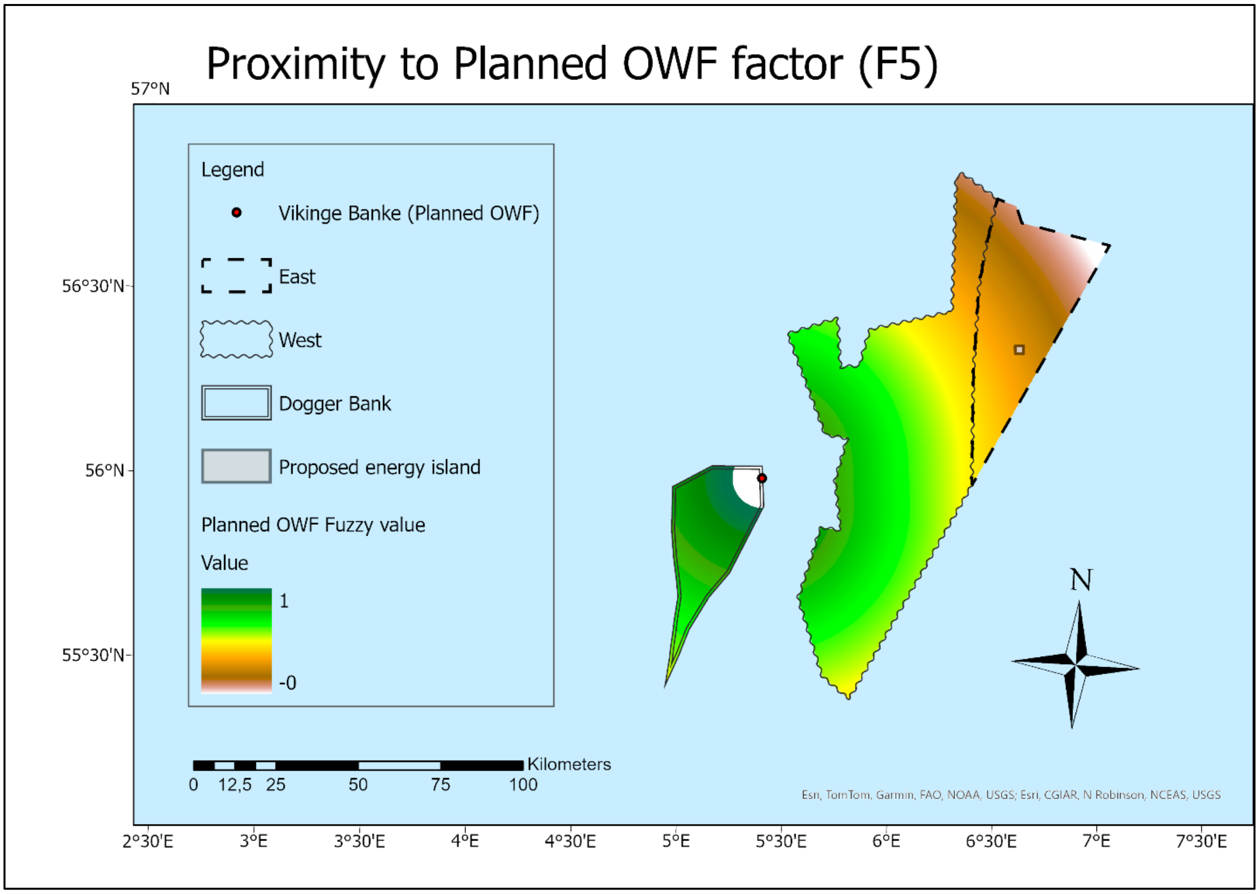

Figure 18. Proximity to planned OWF factor map

Table 11. Mean membership value for each attribute factor map (summary)

Factor attribute	Mean membership value
F1 - Sand lance	0.9018
F2 - Windspeed 100m height	0.5028
F3 - Depth	0.5310
F4 - Distance to shore	0.6129
F5 - Proximity to planned OWF	0.5472

5.4 Calculation of Weights

Following the constraint analysis, the weights for the factor attributes were calculated in the three different scenarios using an AHP approach. Equal weights were simply calculated by dividing the integer one by the number of factor attributes (five). Hence, all factor attributes were given the same importance (Table 12).

Table 12. Equal weights

Factor attribute	**Weight**
F1 - Sand lance	0.20
F2 – Windspeed 100m	0.20
F3 – Depth	0.20
F4 – Distance to shore	0.20
F5 – Proximity to planned OWF	0.20
Sum	1.00

5.5 The Ecological Importance Scenario

Below are shown the used judgement values in the comparison matrix for the ecological scenario and the derived weights calculated by the author in Tables 13 and 14 respectively. The actual calculation of weights (consecutive steps) is described in detail in "A8-1: Weights – Ecological Importance Scenario" in the Appendix section.

In the comparison matrix, the sand lance factor was given an "*Extreme importance*" (9) over the windspeed factor, the distance to shore factor and the proximity to a planned OWF. The sand lance was given an "*intermediate*" value between moderate and strong (4) over the depth factor. The depth factor was given an "*Essential or strong importance*" (5) over the distance to shore factor and the proximity to a planned OWF. An *"Equal importance"* (1) was given to a factor compared to itself or another factor with an equal importance (Table 13).

Table 13. Comparison matrix - ecological importance

Factors	**F1**	**F2**	**F3**	**F4**	**F5**
F1 – Sand lance	1	9	4	9	9
F2 - Windspeed	1/9	1	1/4	1	1
F3 - Depth	1/4	4	1	5	5
F4 – Distance	1/9	1	1/5	1	1
F5 - Proximity	1/9	1	1/5	1	1
Sum	**1.583**	**16**	**5.65**	**17**	**17**

Table 14. Calculation of eigenvector (weights) - ecological

Factors	F1	F2	F3	F4	F5	Weights
F1	0.632	0.562	0.7080	0.529	0.529	0.592
F2	0.070	0.062	0.0442	0.059	0.059	0.059
F3	0.158	0.250	0.1770	0.294	0.294	0.235
F4	0.070	0.063	0.0354	0.059	0.059	0.057
F5	0.070	0.063	0.0354	0.059	0.059	0.057
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

5.5.1 Validation of Weights for the Ecological Scenario

The same calculation of eigenvector was performed in MATLAB and PriEst software which resulted in slightly different weight values (Table 15). Since both MATLAB and PriEst software came out with slightly different results and are expected to be more accurate, their weights were used in the ecological importance scenario.

Table 15. Ecological weights in MATLAB and PriEst

Factors	Weight
F1	0.600
F2	0.058
F3	0.230
F4	0.056
F5	0.056
Sum	**1.000**

5.5.2 Consistency Ratio (CR) for the Weights in the Ecological Scenario

To validate whether the calculated weights were consistent before applying them in the WLC operation, a consistency ratio (CR) calculation was performed. A CR ≤ 0.10 is considered acceptable. If the CR is > 0.10 a re-evaluation of the judgements is necessary. A detailed calculation of the eigenvalue, consistency index (CI) and CR is described in "A8-2: Calculation of

Eigenvalue (*λmax*), CI and CR - Ecological" in the Appendix section. The CR for the ecological scenario in this study was 0.015 which was considered acceptable.

5.6 The Economic Importance Scenario

A similar method was used to calculate the weights in the economic importance scenario, however, with an emphasis on economic factors such as windspeed and distance to shore. The comparison matrix and the derived weights calculated by the author for the economic scenario is shown in Table 16 and 17 respectively. A detailed calculation of the weights is described in "A8-3: Weights – Economic Importance Scenario" in the Appendix section.

In this scenario, the windspeed factor was given an *"Extreme importance"* (9) over the sand lance factor, and an *"Essential or strong importance"* (5) over proximity to a planned OWF factor. The depth was given an *"Essential or strong importance"* (5) over the sand lance factor, and an "*Intermediate"* value between moderate and strong (4) over the proximity to a planned OWF factor. The distance to shore factor was given an *"Extreme importance"* (9) over the sand lance, a *"Moderate importance"* (3) over the depth factor, and an *"Essential or strong importance"* (5) over the proximity to a planned OWF factor. The proximity to a planned OWF factor was given a *"Moderate importance"* (3) over the sand lance factor.

Table 16. Comparison matrix - economic importance

Factors	**F1**	**F2**	**F3**	**F4**	**F5**
F1	1	1/9	1/5	1/9	1/3
F2	9	1	2	1	5
F3	5	1/2	1	1/3	4
F4	9	1	3	1	5
F5	3	1/5	1/4	1/5	1
Sum	**27**	**2.81**	**6.45**	**2.64**	**15.33**

Table 17. Calculation of eigenvector (weights) - economic

Factors	**F1**	**F2**	**F3**	**F4**	**F5**	**Weights**
F1	0.037	0.040	0.031	0.042	0.022	0.034
F2	0.333	0.356	0.310	0.378	0.326	0.341
F3	0.185	0.178	0.155	0.126	0.261	0.181
F4	0.333	0.356	0.465	0.378	0.326	0.372
F5	0.111	0.070	0.039	0.076	0.065	0.072
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

5.6.1 Validation of Weights for the Economic Scenario

The same calculation of eigenvector was performed in MATLAB and PriEst software which resulted in slightly different weight values (Table 18). Since both MATLAB and PriEst software came out with slightly different results and are expected to be more accurate, their weights were used in the economic importance scenario.

Table 18. Economic weights in MATLAB and PriEst

Factors	Weight
F1	0.034
F2	0.339
F3	0.181
F4	0.375
F5	0.071
Sum	**1.000**

5.6.2 Consistency Ratio (CR) for the Weights in the Economic Scenario

A detailed calculation of the eigenvalue, consistency index (CI) and CR is described in "A8-4 Calculation of Eigenvalue *(λmax*), CI and CR - Economic" in the Appendix section. The CR for the economic scenario in this study was 0.025 which was considered acceptable.

5.7 Suitability Index (SI) Maps and Reclassified SI Maps for the Three Scenarios

In the WLC process, the calculated weights were applied in the Weighted Sum tool operation for each scenario and SI maps were generated. The equal importance SI map, the ecological importance SI map and the economic importance SI map are shown in "A9: Suitability Index Maps for the Three Scenarios" in the Appendix section. Following the generation of SI maps for the three scenarios, the SI maps were reclassified into three classes: Low Suitability (SI<0.5), Medium Suitability (0.5 <SI<0.75) and High Suitability (SI>0.75). The reclassified SI maps are shown in Figures 19-21 below.

5.7.1 Equal Weights Reclassified SI Map

In the equal weights reclassified SI map (Fig. 19), the entire section of the West and the East sections were identified as medium suitable areas. However, small areas in the central East section of the proposed energy island and a spot nearby were identified as highly suitable.

The high suitability area was found to be 34.86 km^2 which equals about 2% of the East section or about 0.5% of the whole study area. The medium suitability area was calculated to 89% of the whole study area. The vast part of the Dogger Bank was identified as a low suitability area except for an area outside the planned OWF. The low suitability area was found to be 11% of the whole study area.

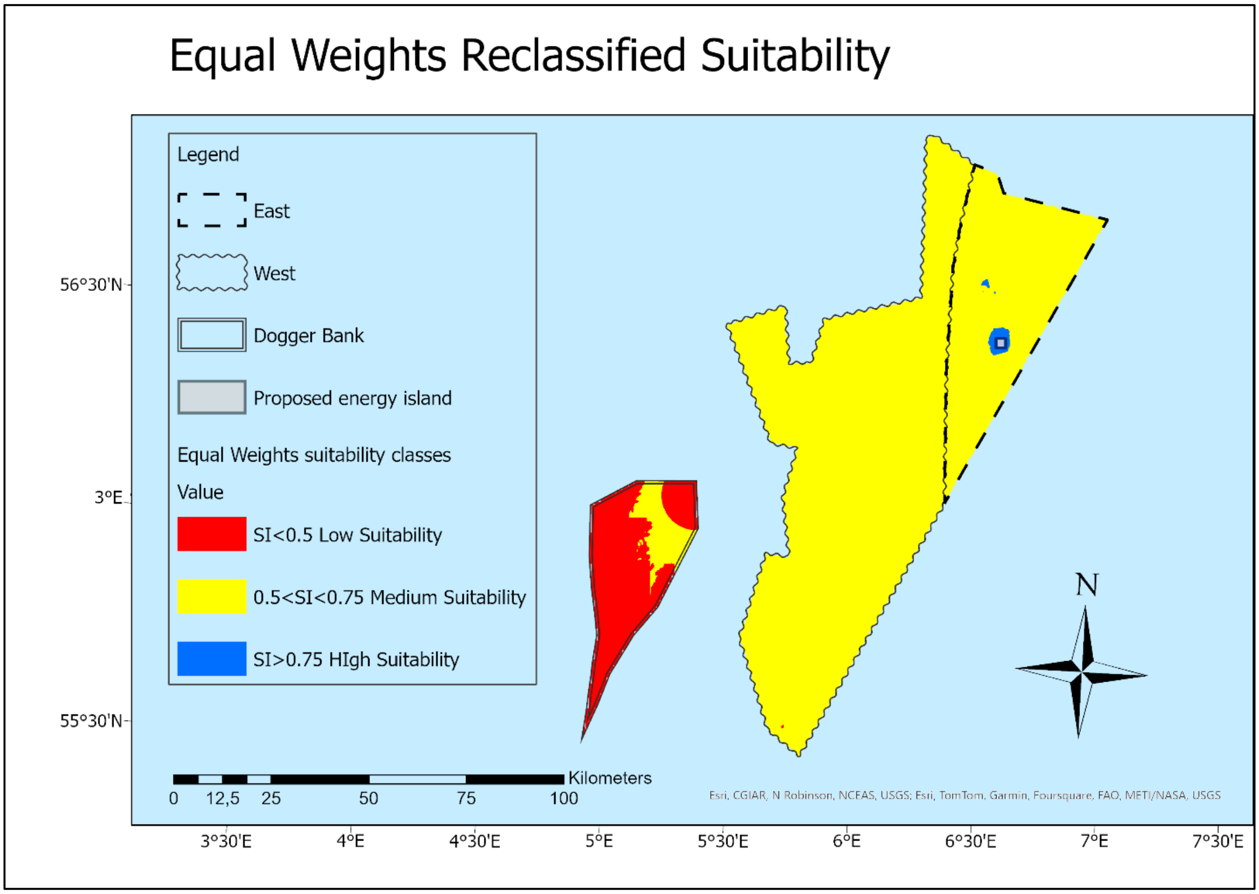

Figure 19. Equal weights reclassified SI map

5.7.2 Ecological Scenario Reclassified SI Map

In the ecological reclassified SI map (Fig. 20), the vast part of the East was identified as highly suitable except for some small areas in the northwestern corner of the section. Also, the West was identified as highly suitable except for the southernmost tip and the western and northern corners of the section and a spot in the center identified as medium suitable. The Dogger Bank was almost split in two - the northern half of the Dogger Bank was identified as a medium suitability area, and the southern/southwestern half identified as a low suitability area. The highly suitable area was found to be about 76.5% of the whole study area. The medium suitable area was found to be about 16.5% of the whole study area and the remaining low suitable area was calculated to be about 7% of the whole study area.

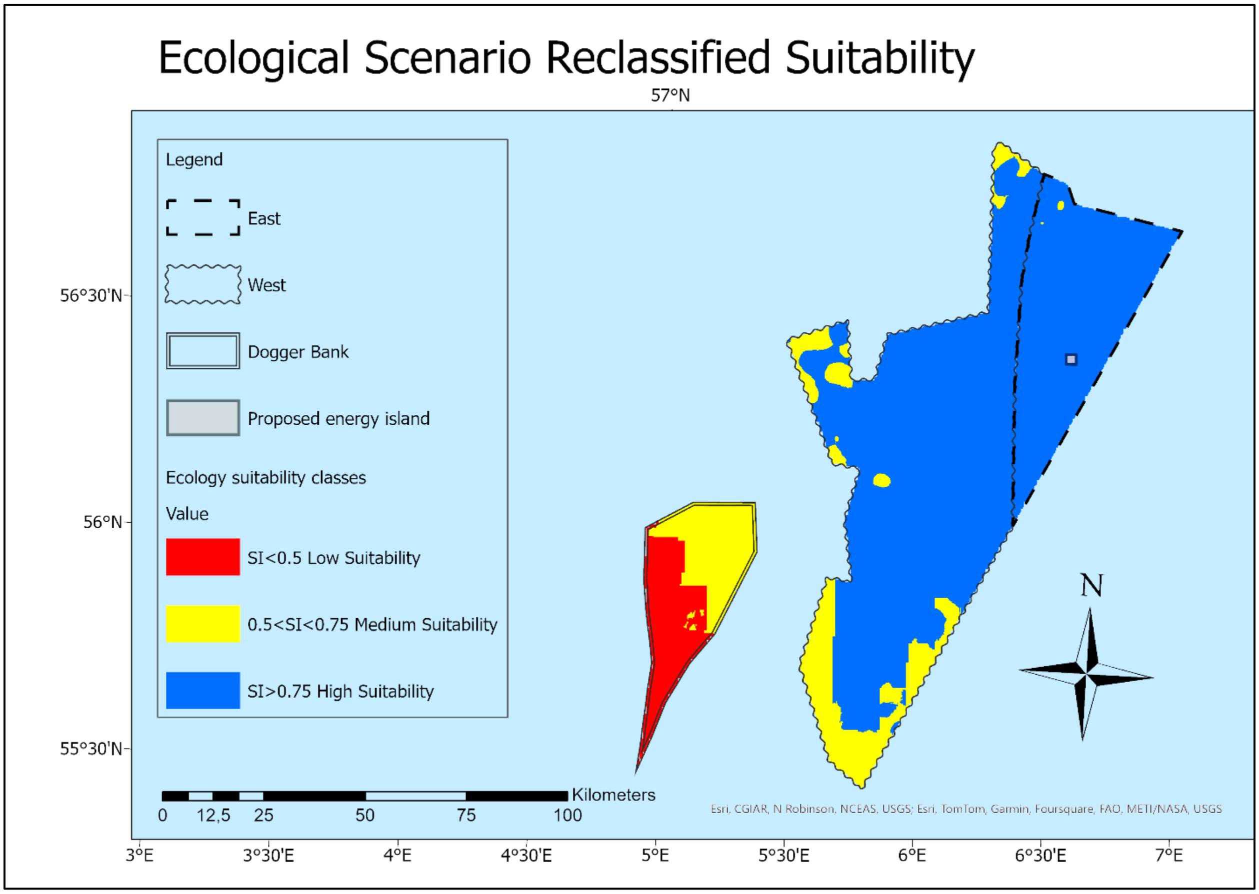

Figure 20. Ecological scenario reclassified SI map

5.7.3 Economic Scenario Reclassified SI Map

In the economic reclassified SI map (Fig. 21), a vast part of the East – located in the northeast corner of the section - was identified as highly suitable. The highly suitable area was calculated to be about 43% of the East section or some 10% of the whole study area. The medium suitable area was identified in the western part of the East section and a major part of the West i.e. the eastern and central part of the West. The medium suitable area was calculated to 58.5% of the whole study area. The remaining part, about 31.5% in the western part of the West section and the entire Dogger Bank were identified as a low suitability area.

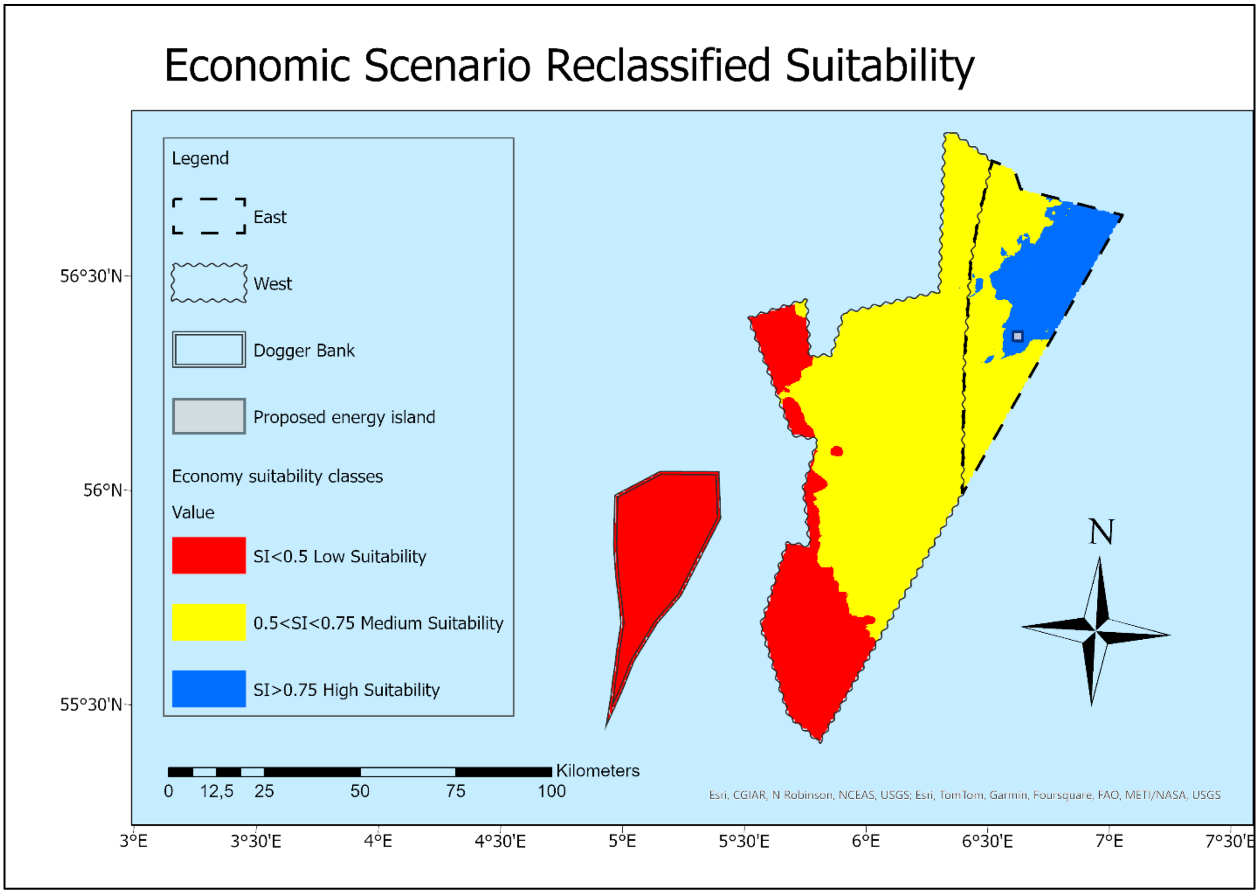

Figure 21. Economic scenario reclassified SI map

5.8 Mean Suitability Index Values for the Three Scenarios

The mean suitability index values (Table 19) were calculated from the SI maps for each scenario ("A9: Suitability Index Maps for the Three Scenarios" in the Appendix section). As can be seen, the ecological scenario had the highest mean SI value at 0.76 across the cells in the study area whereas the economic scenario had the lowest mean SI value at 0.57 based on the weighting above. The mean values were prior to the Boolean masking i.e. multiplication of the composite constraint map.

Table 19. Mean suitability index values for the scenarios

Suitability Index Map	**Mean SI value**
Equal importance scenario	0.62
Ecological importance scenario	0.76
Economic importance scenario	0.57

5.8.1 Suitability Statistics for the Reclassified SI Maps

After the reclassification of the SI maps, the number of cells of "High", "Medium" and "Low Suitability" in square kilometers were calculated relative to the whole study area (Table 20). The term 'Accepted Suitability' which is the 'Medium' and 'High Suitability' added together are shown in the last column.

The ecological importance scenario had the largest area of 'Accepted Suitability' at about 6590 km² due to a large area of 'High Suitability' followed by the equal importance scenario at about 6342 km². The economic importance scenario had the smallest 'Accepted Suitability' area at about 4854 km², mostly due to a very small area of 'High Suitability'. The calculations are shown in "A10: Calculation of reclassified SI maps" in the Appendix section.

Table 20. Suitability statistics for reclassified SI maps

Policy Scenario	Area of 'High Suitability' (km²)	Area of 'Medium Suitability' (km²)	Total area of 'Accepted Suitability' (km²)
Equal importance	7086 * 0.005 = **35.43**	7086 * 0.89 = **6306.5**	**6341.9**
Ecological importance	7086 * 0.765 = **5420.8**	7086 * 0.165 = **1169.2**	**6590**
Economic importance	7086 * 0.10 = **708.6**	7086 * 0.585 = **4145.3**	**4853.9**

5.9 Overall Suitability Maps

Finally, the overall suitability maps were generated by multiplying the SI maps with the composite constraint map which masked out or nullified the unsuitable areas from the constraint analysis.

The equal weights overall suitability map is shown in Fig. 22. The whole Dogger Bank section and a major section of the West were masked out and identified as unsuitable. A few specks in the central of the West and an even larger area in the East were identified as highly suitable or medium suitable. The maximum SI was 0.7749 and the mean SI 0.1408.

The ecological scenario overall suitability map is shown in Fig. 23. Again, like the equal overall suitability map, the whole section of the Dogger Bank was identified as unsuitable just as the West section except for small areas in the central part which were identified as medium to highly suitable. The East section had areas in the central part identified as medium to highly suitable and the northwestern corner and southernmost tip identified as unsuitable. The maximum SI value was 0.9149 and the mean SI 0.1685.

The economic scenario overall suitability map is shown in Fig. 24. Like the other two scenarios, the economic scenario mapped an unsuitability in the whole Dogger Bank section and a major part of unsuitability in the West section except for some parts in the north and central area identified as primarily medium suitability. However, the East section had a larger and denser area of high suitability in the central part around the proposed energy island and further up towards the northeast corner due to lower depth and a less distance to shore. The maximum SI was 0.8315 and the mean SI equaled 0.1453.

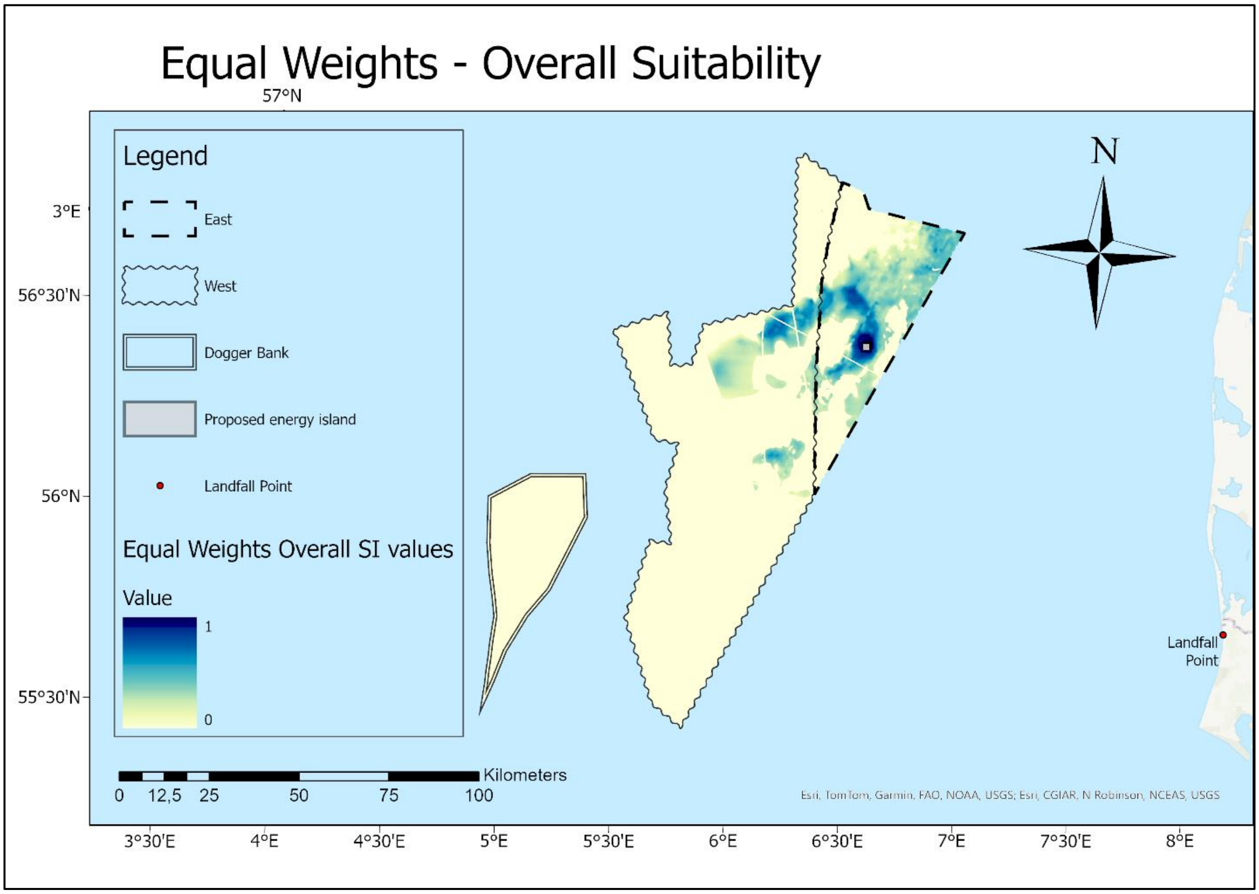

Figure 22. Equal weights overall suitability map

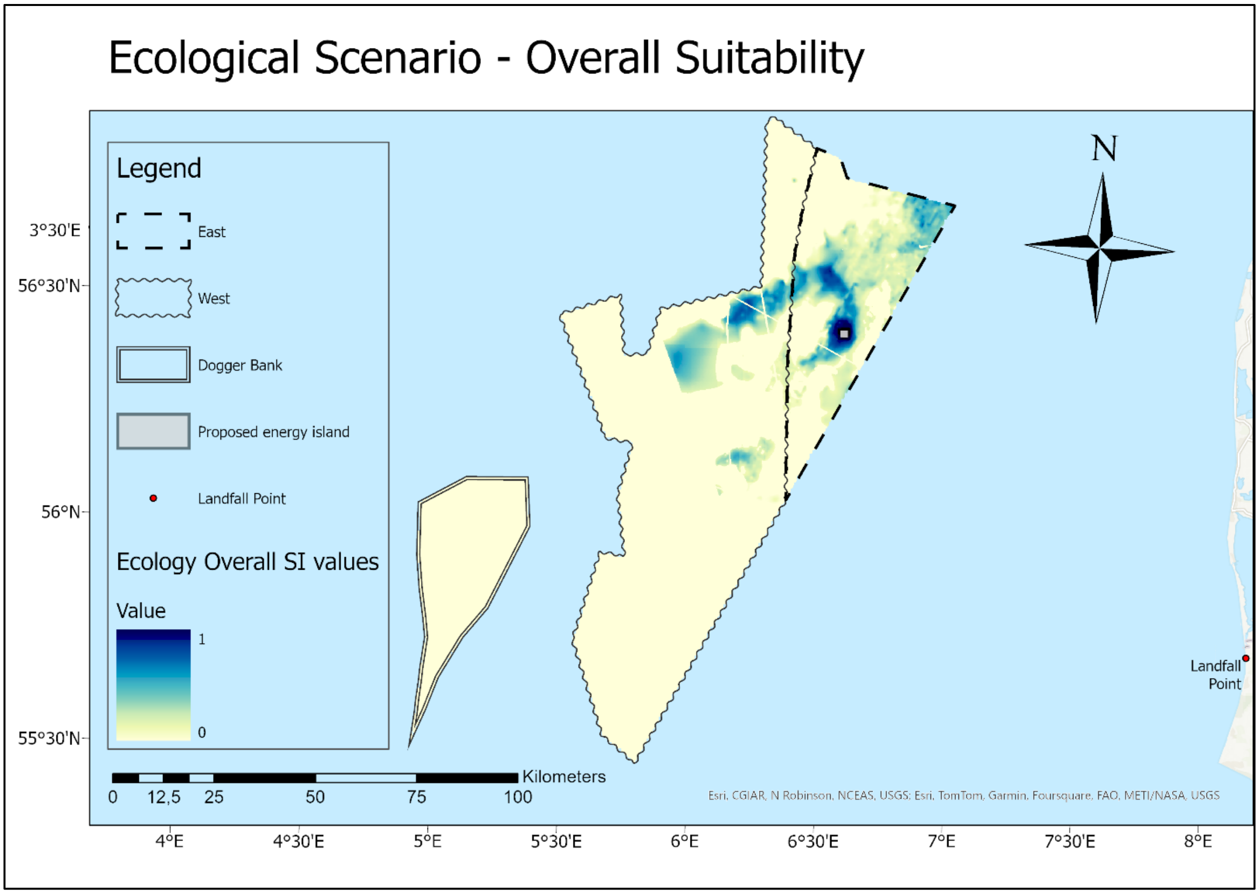

Figure 23. Ecological scenario overall suitability map

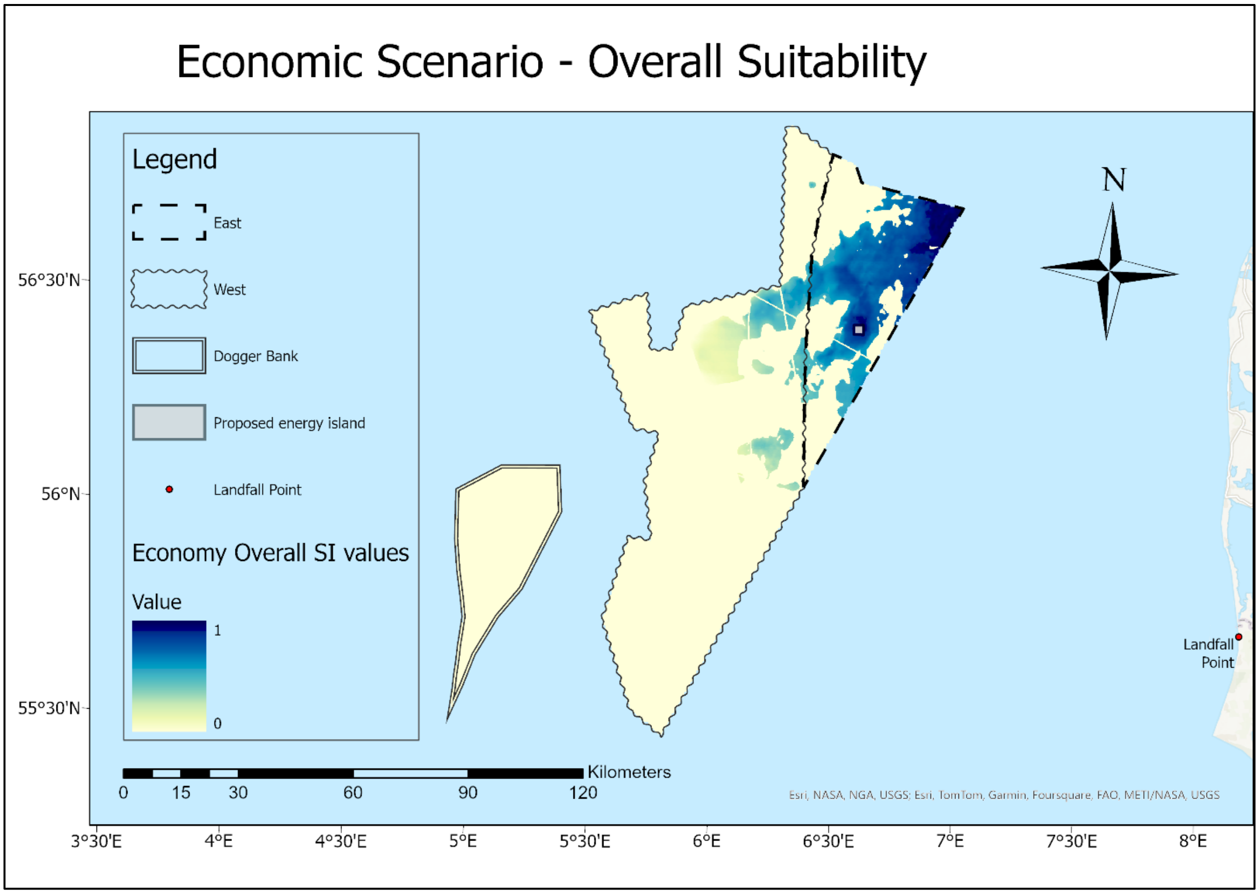

Figure 24. Economic scenario overall suitability map

5.10 Ranking of Alternatives (Locations)

As can be seen from the above analysis, the East had the best overall suitability in all three scenarios: equal weights, an ecological and an economic priority with a maximum SI at 0.77, 0.91 and 0.83 respectively, and a mean SI at 0.14, 0.17 and 0.15 (rounded) respectively. Furthermore, in the reclassified SI map, the East had areas of high suitability in all three scenarios ranging from small areas in the equal weight scenario at the proposed energy island, to almost the entire section in the ecological scenario and a 43% coverage in the economic scenario.

The West had the second-best overall suitability in both the equal weights, the ecological and the economic priority with a maximum SI at 0.75, 0.89 and 0.75 respectively, and a mean SI at 0.077, 0.094 and 0.074 (rounded) respectively. The West had a vast area of high suitability in the ecological reclassified SI map, but the area was nullified into a non-suitability after the Boolean masking with only some areas in the central section identified as medium to high suitability remaining.

Finally, the Dogger Bank had the least performance with a maximum SI of 0 in all three scenarios and was therefore nullified into a non-suitability area.
Besides, the best location in all three scenarios was indeed situated at the proposed energy island location or nearby in the East section with a distance to the landfall point at about 125 km. The ranking of the locations is shown In Table 21 below.

Table 21. Ranking of alternatives

Section	**Suitability class**	**Equal weights**	**Ecological priority**	**Economic priority**
The East	No suitability to high suitability	1	1	1
The West	No suitability to high suitability	2	2	2
The Dogger Bank	No suitability	3	3	3

5.11 Calculation of The Optimal Site(s)

As a result of this study, the most obvious location was found in the East section, and in all three scenarios the area with the highest mean SI was indeed the planned location by the government. Furthermore, the minimum extent was found in the equal weights and the ecological scenario which was calculated freely with the ArcGIS Pro measure tool to about 40 km^2. In the economic scenario the extent was calculated to about 60 km^2. All three calculations were made with a minimum buffer distance of about 1000m away from the non-suitability area.
In all three scenarios, a “new” highly suitable location was identified northwest of the planned location. The location is slightly smaller and partly connected to the planned location. The new location has the shape of a banana in combination with the planned location and could be an alternative option to the planned location or simply an addition. Moreover, in the economic scenario, another highly suitable area was identified in the northeastern corner of the East section. The area is somewhat connected to the planned location and a larger area, but it was only identified in the economic scenario.

5.12 Sensitivity Analyses

A sensitivity analysis was performed for both the ecological and the economic scenario. The equal weights scenario was not included as the sensitivity analysis was only made in relation to the scenarios with different importance.

In the ecological importance scenario, the factors with an *extreme importance* (9) assigned, such as the sand lance over the windspeed, the distance and the proximity factors, were lowered to a *very strong importance* (7). The factor with an *essential or strong importance* (5) assigned, such as the depth over the distance and the proximity factor, was lowered to the intermediate value (4) between a *moderate importance* and an *essential to strong importance*. The factor with an intermediate value between a *moderate importance* and an *essential or strong importance* (4), such as sand lance factor over the depth factor was lowered to a *moderate importance over one another* (3). The comparison matrix and the complete steps in the weight calculation are shown in "A11-1: Ecological Scenario Weights - Sensitivity Analysis" in the Appendix section. The result map of the ecological sensitivity analysis is shown in Figure 38 in the Appendix section.

As can be seen, the ecological sensitivity analysis map is very similar to that of the original ecological overall suitability map except the SI values was changed slightly i.e. the maximum SI in the sensitivity analysis was lowered to 0.9012 compared to 0.9149 in the original ecological overall suitability map. The mean SI in the ecological sensitivity analysis was lowered to 0. 1652 compared to 0.1685 in the original ecological scenario.

In the economic importance scenario, the factors with an *extreme importance* (9) assigned, such as the windspeed over the sand lance and distance to shore factor over the sand lance were lowered to a value with a *very strong importance* (7). Factors with an *essential or strong importance* (5) assigned such as windspeed over proximity, and depth over the sand lance and distance to shore over the proximity factors, were lowered to an intermediate value (4) between a *moderate importance* and an *essential to strong importance*. The comparison matrix and the complete steps in the weight calculation are shown in "A11-4: Economic Scenario Weights - Sensitivity Analysis" in the Appendix section. The result map of the economic sensitivity analysis is shown in Figure 39 in the Appendix section.

Again, the sensitivity analysis map was identical with the original overall suitability map for the economic scenario except that the overall SI values were slightly lower in the sensitivity analysis. In the sensitivity analysis, the maximum value was calculated to 0.8250 and the mean SI was 0.1447. Similar values in the original economic scenario were 0.8314 and 0.1453 for the maximum SI and mean SI respectively.

6. Discussion

This study aimed at finding the most optimal location for an energy island in the Danish North Sea. The study area included three sections: The East, The West and The Dogger Bank sections within the Danish EEZ of the North Sea. Totally nine attributes with their underlying criteria were analyzed either as constraint, factors or both to identify the best location in three scenarios: an equal weights priority where all attributes were allotted equal weights, an ecological priority with a focus on the sand lance ecosystem and an economic priority with an emphasis on economic factors such as distance to shore and windspeed to reduce cable length and optimize the energy production.

An analytic hierarchy process (AHP) which is a multicriteria decision analysis (MCDA) approach was implemented to calculate weights and arrive at the optimal result. The result of the study would also test against the proposed energy island by the government and either confirm or compromise the planned location. Furthermore, the optimal location could help define the certain type of energy island structure.

The attributes displayed as map layers consisted of sand lance density, vessel traffic routes, sea depth, windspeed at 100m height, seabed sediments, distance to shore, cables and pipelines, shipwrecks and UXO and proximity to a planned OWF. Attributes which could be relevant e.g. wave height, sand fluctuation and underwater currents, birds and bats, fisheries, sea mammals and elasmobranchs etc. were not included in this analysis as some of them would be related to the used attributes and therefore redundant.

Other attributes like visual effects and flicker from the wind towers, wake effects, noises and electromagnetic interference during operation were not included due to time constraints of the master thesis timeline and were expected to be beyond the scope of this study. However, inclusion of these omitted attributes would modify the weights and thereby influence the result. Furthermore, according to Malczewski and Rinner (2015), the attributes in an MCDA should be kept at a minimum e.g. less than ten attributes to be tractable and have a focus. The attributes were either geographical data from other data sources or numerical data mapped by the author and processed and analyzed in ArcGIS Pro computer software.

In the constraint analysis, each attribute was evaluated on a cell-to-cell basis either as suitable (value 1) or unsuitable (value 0) which would exclude the area from further analysis. Some attributes had a strong impact on the analyses e.g. the sea depth which excluded 74% of the study area leaving only 26% of the area with a depth less than 40m which was considered the maximum depth for an energy island in this study.

The sand lance density attribute excluded 20% of the study area including the whole Dogger Bank section. A reasonable explanation for high sand lance density at the Dogger Bank could be perfect conditions for the species such as a less depth, a sandy sea bottom, optimal temperatures and currents and an abundance of copepods etc.

The seabed attribute excluded some 28% of the study area – primarily in the southern part of the West section due to a vast area of sediments such as clay, silt and mud which was not considered a solid foundation for an energy island and surrounding OWF's. The remaining 72% had a coverage of sand, coarse sand, till and diamicton which were considered a suitable foundation for an energy island.

The vessel traffic constraint had an exclusion zone at 14% - primarily belts across the southern part of the West section and across the central Dogger Bank. The East section was not affected by vessel traffic, but a vessel route was identified along the eastern boundary right beyond the East section.

The cables and pipelines attribute only excluded 2.6% of the study area. The West had the largest share of cables and pipelines at 83%. The East and the Dogger Bank had a share at about 8% and 9% respectively.

The composite constraint which are all the individual constraint maps overlaid identified an exclusion of 80% of the whole study area.

On the other hand, some attributes had only an inferior impact on the analysis e.g. the shipwreck and UXO and proximity to a planned OWF attributes which only excluded an area about 1% or less each of the entire study area.

In the factor analysis, each attribute was evaluated on a cell-to-cell basis using a fuzzy membership function describing its degree of suitability on a continuous scale ranging from 0 to 1 including all real numbers in between where 0 equaled no suitability and 1 equaled ideal location.

The sand lance factor identified a very low fuzzy value i.e. degree of suitability in the Dogger Bank section due to the high density of sand lance as mentioned above compared to the rest of the study area.

The windspeed factor had fuzzy values close to 1, indicating a high wind resource, in the northern parts of the East and the West sections and values close to 0 in the southern parts of especially the West and the Dogger Bank.

The depth factor had values closest to 1 in central parts of both the East, the West, and the Dogger Bank indicating a shallower depth.

Not surprisingly, the distance to shore factor had fuzzy values close to 1 in areas nearest the landfall point and decreasing further out west. Conversely, the proximity to the planned OWF had values close to 1 right outside the buffered section of the planned OWF and decreasing values towards the east and the Danish west coast.

Based on the factor analysis, the weighted linear combination (WLC) was performed where all factor maps were assigned weights derived from the AHP in two scenarios: an ecological priority and an economic priority. The equal weights scenario was not included in the AHP process as the weights were distributed evenly i.e. a weight at 0.2 on all attributes.

The WLC operation generated three different suitability index maps: an equal weights SI map, an ecological scenario SI map and an economic scenario SI map. The three SI maps were in turn reclassified in three classes: Low suitability ($SI<0.5$), medium suitability ($0.5<SI<0.75$) and high suitability ($SI>0.75$). In other words, an $SI>0.5$ would be considered ‘Acceptable’. Latinopoulos and Kechagia (2015) had slightly different SI thresholds compared to this study: low suitability $SI \leq 0.5$, medium suitability $0.5<SI<0.7$ and high suitability $SI \geq 0.7$.

The reclassified SI map showed large differences e.g. in the equal weights scenario, the East and the West sections were identified as medium suitable areas. More interestingly, in the ecological scenario, the same sections were largely identified as highly suitable areas. The Dogger Bank was identified as low to medium suitable in the equal weights and the ecological scenario but in the economic scenario it was completely identified as a low suitability area.

The major findings can be seen in the result of the overall suitability analysis i.e. where the composite constraint map and all the weighted factor maps were overlaid. Interestingly, the ecological scenario had the highest SI value at 0.91 compared to the economic scenario with an SI at 0.83 and the equal weights scenario with an SI at 0.77. Whereas the equal weights and ecological scenario had almost the same pattern, the economic scenario, however, had the largest extent of high suitability.

Another interesting point is that the East section performed the best in all three scenarios which can be ascribed to facts such as a low sand lance density, a short distance to shore, relatively shallow depths, good seabed conditions and a relatively good wind resource. On the other hand, the Dogger Bank was masked out i.e. identified as a non-suitable area in all three scenarios primarily due to a high sand lance density, a long distance to shore and a weaker wind resource although the depth and seabed conditions were considered relatively good. This finding will therefore answer the second research question whether an ecological priority will result in extra cable length and following costs as an ecological priority did not identify a location further west beyond the East section. Conversely, an economic priority will not result in a location with a high sand lance density as the Dogger Bank was masked out in the economic scenario. Thus, the third research question was answered.

As previously mentioned, the AHP was the chosen MDCA for this study. Other MCDA’s such as *outranking methods* e.g. PROMETHEE and ELECTRE and *discriminant functions* e.g. the LDA approach and *function-free models* e.g. the DRSA approach exist. However, the AHP was considered appropriate in this study due to its simplicity and intuitive approach in decomposing decision problems in a hierarchy model which can be helpful for decision makers with limited experience in MCDA techniques. Furthermore, the AHP approach entails other benefits as it is considered a flexible approach where criteria can be added or removed and the information is based on subjective judgements rather than measurement performances (Bobeck, 2017). Besides, the AHP has been applied in similar energy planning studies either separately (Chaouachi et al., 2017) or in combination with WLC (Latinopoulos & Kechagia, 2015; Bobeck, 2017). The last two studies aimed at identifying onshore wind farm locations in Greece and Australia respectively.

In contrast, Fetanat & Khorasaninejad (2015) applied a hybrid of fuzzy ANP[17], a fuzzy DEMATEL[18] and a fuzzy ELECTRE assessing OWF site selection in the Persian Gulf. Ziemba (2021) applied a TOPSIS approach when assessing the planned OWF investments in Poland. It should be noted that the other MCDA's have different underlying mathematical computations which may yield different results.

It is recognized that the AHP has been subjected to criticism. For instance, some analysts claim that the 1-9 Saaty scale may be interpreted differently or inconsistently by decision makers which could lead to inaccurate distribution of weights. However, as mentioned earlier, the consistency ratio (CR) can counteract these pitfalls when done properly. Also, the AHP is sometimes used on an ad-hoc basis with a limited theoretical foundation and underlying assumptions are sometimes ignored and the set of data may be incomplete and redundant (Malczewski, 2000). Malczewski, however, acknowledged that it can be difficult to achieve the underlying assumptions in a spatial decision context i.e. to achieve a set of criteria that is decomposable and non-redundant. Moreover, there is a risk of rank reversal in the AHP when using the rank aggregation instead of the score aggregation (Teknomo, 2016).

The judgements in the ratio matrix in this study were made solely on account of the author's subjective choices with a CR less than 0.10 which were considered acceptable. As a limiting factor, it should be noted though that the AHP approach relies on subjective judgements for weighting attributes and different stakeholders might assign different weights leading to different outcomes

A linear membership function was found appropriate for this study as the relationship between the attributes were assumed linear given the spatial context. Other non-linear membership functions such as the logistic sigmoidal (s-shaped) or the exponential (j-shaped) function were found to be less appropriate in the study as it would be difficult to determine non-linearity in this spatial context. It should be emphasized though that the linear relationship between attributes and suitability may not always be accurate. Furthermore, a linear membership function has also been used in similar studies (Hansen, 2005; Latinopoulos et al., 2015; Bobeck, 2017).

The obtained data were either vector, raster or numerical data. The vector data was converted to raster during the geoprocessing and resampled to a cell size of 100m. Other studies applied cell sizes at 150m (Latinopoulos & Kechagia; Bobeck, 2017) and as low as 50m (Hansen, 2005). However, these studies assessed onshore windfarm site suitability.

The spatial resolution at 100m in this study was considered optimal as it would be a compromise between the above studies. Besides, Malczewski (2000) emphasized that a disaggregated high

[17] Analytic Network Process (ANP) - a modification of AHP.

[18] Decision Making Trial and Evaluation Laboratory (DEMATEL).

resolution in a WLC was generally preferred. Also, Martínez-Gordón et al. (2021) underscored the benefits of a high spatial resolution in energy modelling.

The issue of modifiable areal unit problem (MAUP) was acknowledged especially in relation to the sand lance data that was based on aggregated data of the years 1980-2013. The mere aggregation of the dataset will inevitably introduce some uncertainties plus the zoning problem where interpolation and aggregation can 'spill over' and affect the adjacent zone, in this case, the East and the West sections. The issue was dealt with to some extent by converting the raster data to point feature data and clipping to the respective sections. The minimum and maximum values of the point feature data for each section were compared to the minimum and maximum values of the raster data. The point data values for the individual sections were identical with that of the raster data and were there considered acceptable.

A sensitivity analysis for both the ecological and the economic scenario was performed to test the robustness of the analysis. Thus, new (Saaty) values were entered in the corresponding comparison matrices. In the ecological sensitivity analysis, the values 9 (e.g. the sand lance factor) were lowered to 7, the values 5 were lowered to 4 and a single value 4 was lowered to 3. In the economic scenario, the values 9 (e.g. the windspeed factor) were lowered to 7, the values 5 were lowered to 4, a single value 4 was lowered to 3, and two values of 3 were lowered to 2. The sensitivity analysis only changed the overall SI maps slightly in both scenarios. In the ecological scenario the maximum SI fell from 0.9149 to 0.9012, and in the economic scenario the maximum SI fell from 0.8314 to 0.8250. The overall pattern with areas of high, medium, low, and non-suitability in both scenarios remained the same. Therefore, the analysis was considered robust.

Overall, this study found that the most optimal location for an energy island based on an overall suitability analysis in all three scenarios would be in the East section and to a lesser degree in the West section. The Dogger Bank was excluded and considered non-suitable in all three scenarios. In both the equal weights scenario and in the ecological scenario the 'hotspot location' i.e. the cell with the highest SI was found at the location planned by the government with an SI value of 0.77 and 0.91 respectively. The only scenario where the planned location was slightly outperformed was in the economic scenario where the hotspot location was found in the northernmost corner of the East section with an SI value of 0.83 due to its proximity to the shore. However, the planned location was still identified as a high suitability area at about 0.80. The area available for an energy island will range from about 40km² in both an equal weights and an ecological scenario to about 60km² in an economic scenario.

A clear signal from this study is the non-suitability of an energy island in the entire Dogger Bank section and the southeastern part of the West due to a high sand lance density in those sections. The Dogger Bank was excluded even though the greater Dogger Bank area (covering the UK, Dutch, German and Danish EEZ) has been proposed in the literature as a potential location (Van der Meijden, 2016; Gerrits, 2017) as well as being assessed in reports (Royal Haskoning DHV, 2017; Energinet, 2017; NSWPH, 2018; Jansen et al., 2022). The latter of which is mainly assessing the investment cost and electricity markets of an offshore windpower hub. Gerrits (2017) mentions a potential location as the Dogger Bank UK EEZ due to shallow waters (~10m) or the northwest of Denmark although with somewhat lower depths (~20m) which on the other hand has a better wind resource – about 10 percent higher than the Dogger Bank. The Gerrits study further points out that Dogger Bank UK EEZ is a designated Natura 2000 area which contains a very large ecological risk and concludes that a hub and spoke (energy island with surrounding OWFs) is most recommendable in the northwest of Denmark which is in line with the result of this study.

In contrast, the North Sea Wind Power Hub Consortium (NSWPH, 2018) finds in its pre-screening based on EIAs and available data no definite obstacles for development of an energy island and related OWFs in the Dutch, German and the Danish sectors of the Dogger Bank. The pre-screening, however, emphasizes the need for further environmental studies to confirm the expectations that: 1. the potential loss and disturbance of the sandbanks are in accordance with the current ecological integrity of the protected areas in relation to Annex I habitats[19], 2. state-of-the-art mitigation measures such as bubble curtains to reduce underwater noise during pile driving and other construction are being utilized to protect fish and sea mammals, 3. long term displacement on fish and sea mammals on population-level, and birds displacement due to collision with windmills on population-level are not significant.
The preliminary assessment of geology and ecology for the NSWPH-project in the Danish EEZ (Energinet, Internal report, 2017) concludes that there are significant ecological values at the Dogger Bank – especially at the slopes – and further investigations must be carried out to ascertain this in more detail. The report underscores that the cross-border effects must be considered in a coordinated procedure between the implicated countries during the permitting process and different locations of an energy island in the area should be investigated in the EIA process.
However, as the Danish government abandoned the idea of building an energy island in the Danish section of the Dogger Bank in 2018 further investigations in that section have been discontinued. On the other hand, the UK already has an ongoing development of three OWFs in its section of the Dogger Bank. The Dogger Bank Wind Farm is being built in three phases A, B and C with a capacity of 1.2GW each or a total capacity of 3.6GW when fully completed.
As mentioned earlier, this present study deviated from other studies of energy islands in the North Sea and the Dogger Bank as the methodology was based on an MCDA and with a certain focus on the sand lance species. The study would likely have yielded a different result with another MCDA or by using no MCDA at all. Also, the judgement in this study was made solely by

[19] Annex I: EU Habitat Directive with a conservation status.

the author's subjective judgements whereas different inputs from other stakeholders or groups would give different results. The AHP is especially designed for group decision making.

Moreover, in this study the ecological factors were given an extreme importance in the ecological scenario and the economic factors were given extreme importance in the economic scenario. Subsequently, the values in both scenarios were lowered proportionally in the sensitivity analyses. If the values had been changed unproportionally in the sensitivity analyses the results might have been more complex and given a different, maybe more unclear map result?

Another interesting point is that the sand lance was given a threshold >0.001 for a non-suitability (0-value) in the constraint analysis. The choice of the threshold was subjective as the CPUE for the whole study area was ranging from -0.004 to 0.095 and a mean of 0.006 (rounded). It was decided to set the threshold below the mean from an ecological point of view and as a precautionary principle i.e. to be as protective of the sand lance species as possible. If the threshold had been raised, it would have changed parts of the Dogger Bank to a suitable area and thus affected the overall suitability map in all three scenarios.

With regards to this study, it is recommended the that the Danish Dogger Bank Section is banned from a potential energy island development in an ecological perspective, or at least restricted to some OWFs with artificial reefs and sustainable fisheries to avoid a collapse in the ecosystem which could have severe consequences, not only for the ecosystem, but also for the local economies around the North Sea region.

The planned location and the optimal location in this study has a depth of ~ 26m which is just above the limit of 25m for a caisson island structure. It should be noted, though, that the 25m limit is not a strict limit for a caisson structure and this solution could still be considered. Another possible island structure is a sand island which could be considered at a depth as low as 40m. The choice of a threshold of 40m depth in this study was based on Fernández-Guillamón et al. (2019) and Energistyrelsen (2022) of which the latter aimed for a depth between 25-40m. The thresholds set for both sand lance (CPUE 0.001) and depth (<40m) were based on specific assumptions and may not reflect all ecological and economic realities.

As of 28 June 2023, a majority in the Danish Parliament has agreed on a re-evaluation of the energy island structure as current calculations for a combined caisson/sand island would be too expensive i.e. above 50 billion DKK (Danish Ministry of Climate, Energy and Utilities, 2023). A cheaper platform solution is being considered which could even have a positive ecological impact as the platform will only have a low footprint on the seabed compared to a high footprint for a combined caisson sand island solution (Fernández-Guillamón et al., 2019). Though, the Danish Parliament majority still emphasizes their ambition for a large-scale energy production expanding from 3GW to 10GW when the island concept is fully implemented.

Even in an economic perspective, from a Danish viewpoint, the present study points at a location in the East section due to its proximity to the Danish west coast and completely rules out the Dogger Bank section. The result location could therefore have both ecological and economic benefits.

The result of this study could support the planning of an expected energy island and its complementary OWFs in mitigating the negative effects or stressors on the sand lance and thus the local ecosystem in the North Sea. In other words, the present study could be a contribution to a strategic environmental assessment (SEA) which is a general analysis on the effects on the ecosystem in the whole North Sea region due to the expansion of the OWFs and energy islands.
The SEA would normally be followed up by an environmental impact assessment (EIA) which analyses the specific area – in this case the East section.

7. Conclusion

The East section was the best alternative in all three scenarios in this study. The East fared moderately better than the West in both the equal weights and the ecological scenario and remarkably better in the economic scenario. The hotspot location in the East was identified at the planned location in all scenarios and thus in line with the government location. However, in the economic scenario, another hotspot was identified in the northeastern corner of the East section. This hotspot had a slightly better SI value as the planned location. A sensitivity analysis for the two scenarios was performed which confirmed the pattern and identified the same location.

7.1 Answers to Research Questions and the Hypothesis

Based on this study, the research questions and hypothesis will be repeated and answered in the following paragraphs:

1. How different will the two scenarios (an ecologic and an economic) be reflected in a MCDA compared to an equal weights scenario?

Answer: The study found a similar pattern between the equal weights scenario and the ecological scenario. The maximum SI value in the equal weights scenario was 0.77 compared to 0.91 in the ecological scenario. The economic scenario was slightly different from the other two scenarios as it had a wider spatial extent of high suitability in the northeast corner of the East section due to a closer distance to shore. The maximum SI value was 0.83. The Dogger Bank section was non-suitable in all three scenarios.

2. Will an ecological priority result in extra cable length (cable costs)?

Answer: The study found furthermore that an ecological priority with an extreme importance on the sand lance and a strong importance on the depth attribute would not result in extra length and thereby extra cable costs as the East section was the overall preferred alternative in the AHP approach and the Dogger Bank, which was the most distant alternative, was excluded.

3. Will an economic priority result in a location with a high sand lance density?

Answer: The study also found that an economic priority with an extreme importance on attributes such as windspeed and distance to shore would not result in a location with a high sand lance density as the preferred locations in the East have a sand lance density below the threshold of 0.001 CPUE.

4. What type of energy island structure (design) would be optimal for the identified location?

Answer: The optimal location at the planned location has a depth at -26m which makes it suitable for a caisson island, a sand island, or a combination but the Danish Parliament is still considering a cheaper platform solution which in fact would benefit the ecology due to a lower footprint on the seabed compared to the other solutions.

Hypothesis:
An *extreme* importance on sand lance habitats and a *moderately strong* importance on the depth attribute and *no* importance on distance to shore will change the planned location of the energy island significantly i.e. a minimum of 20 km.

Answer: The hypothesis was tested in the ecological scenario which found that the hotspot i.e. the cell with the highest SI was at the proposed location for an energy island and not further away. The location has an area of about 40 km^2 and a perimeter at about 24 km. As the optimal location was identified at the planned location, the hypothesis that the planned would change significantly i.e. minimum 20 km from the planned location would therefore be falsified.

7.2 Emerging New Research Questions

In 2019, 3.6 GW of the European offshore wind capacity was installed of which the North Sea accounted for 77% of the production. Production is expected to increase with up to 80% in the close future (Jansen et al., 2022). As the development of the OWFs and potential energy islands are increasing, the need to investigate the cumulative effects of this expansion and the impact on the ecology become more urgent.

Hence, new research questions will arise e.g. How much will the energy expansion in combination with climate changes affect the sand lance population and the ecosystem in the North Sea? Will the ongoing OWF development in the UK section of the Dogger Bank have “spill-over effects” in the other Dogger Bank sections which are not being developed? Will the mainland grid be able to “absorb” the added energy from the planned OWFs and expected energy islands?

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Appendix

A1: Transmission typologies

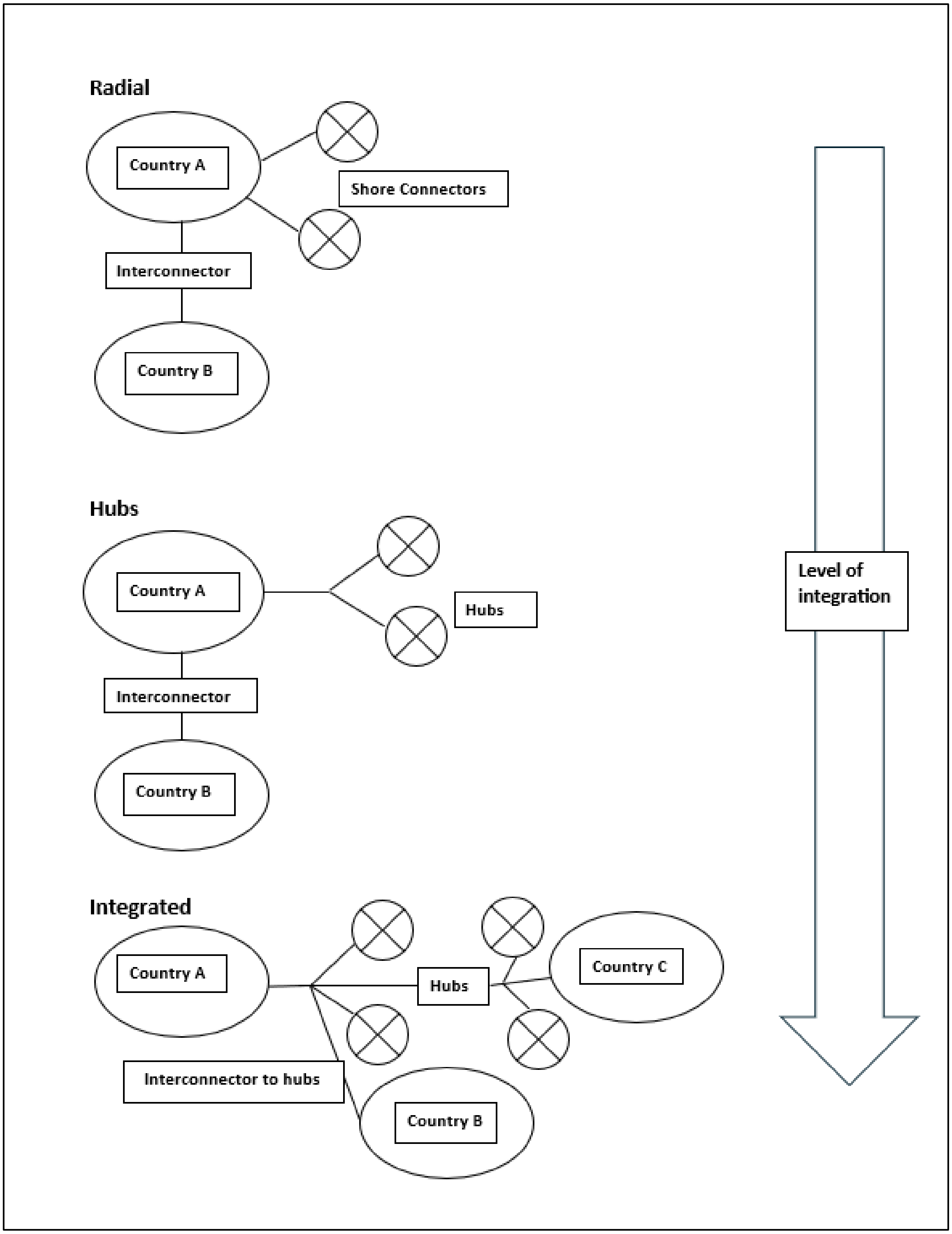


Figure 25. Transmission typologies re-drawn by author (inspired by Dedecca et al., 2016)

A2: Comparison of MADM and MODM approaches

Table 22. MODM and MADM characteristics

Properties:	MODM	MADM
Objectives	Explicitly defined	Implicitly defined
Attributes	Implicitly defined	Explicitly defined
Constraints	Explicitly defined	Implicitly defined
Alternatives	Infinite or very large	Finite or small
Decision maker's control	Significant	Limited
Typical data structure	Vector data	Raster data
Relevance	Design/search	Evaluation/choice

A3: Windturbine foundations

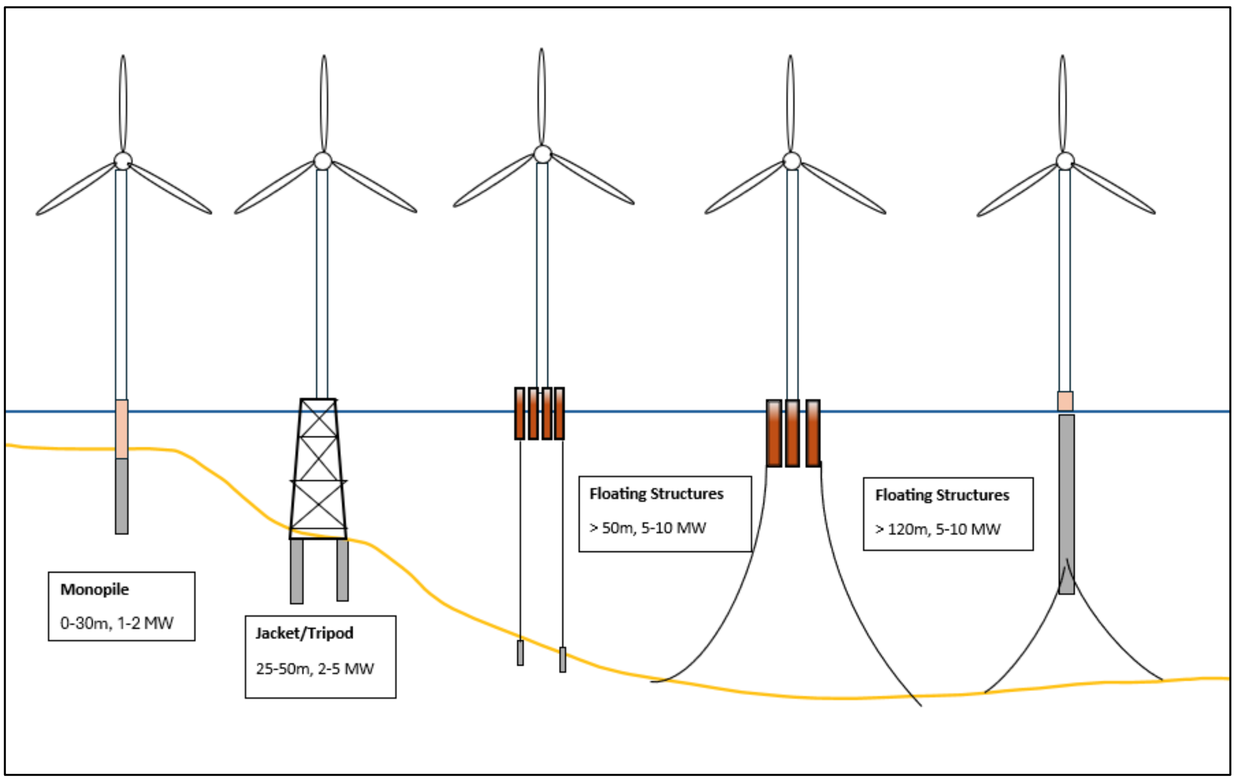


Figure 26. Types of offshore windturbine foundations re-drawn by author (inspired by Bailey et al., 2014)

A4: Decommissioning options for offshore structures

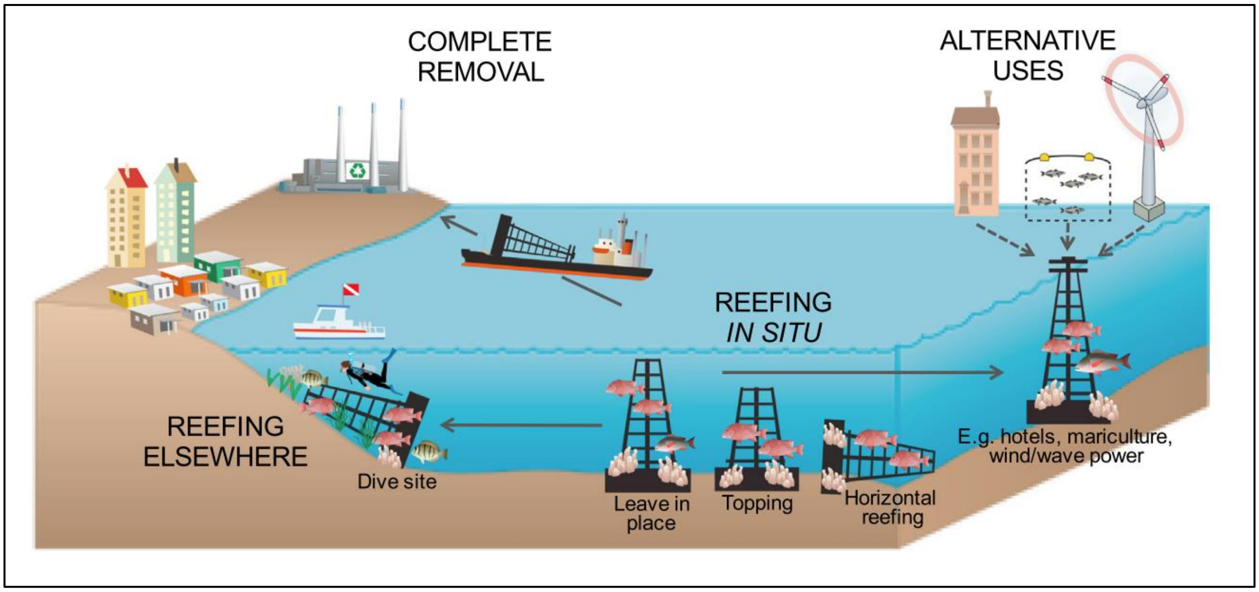
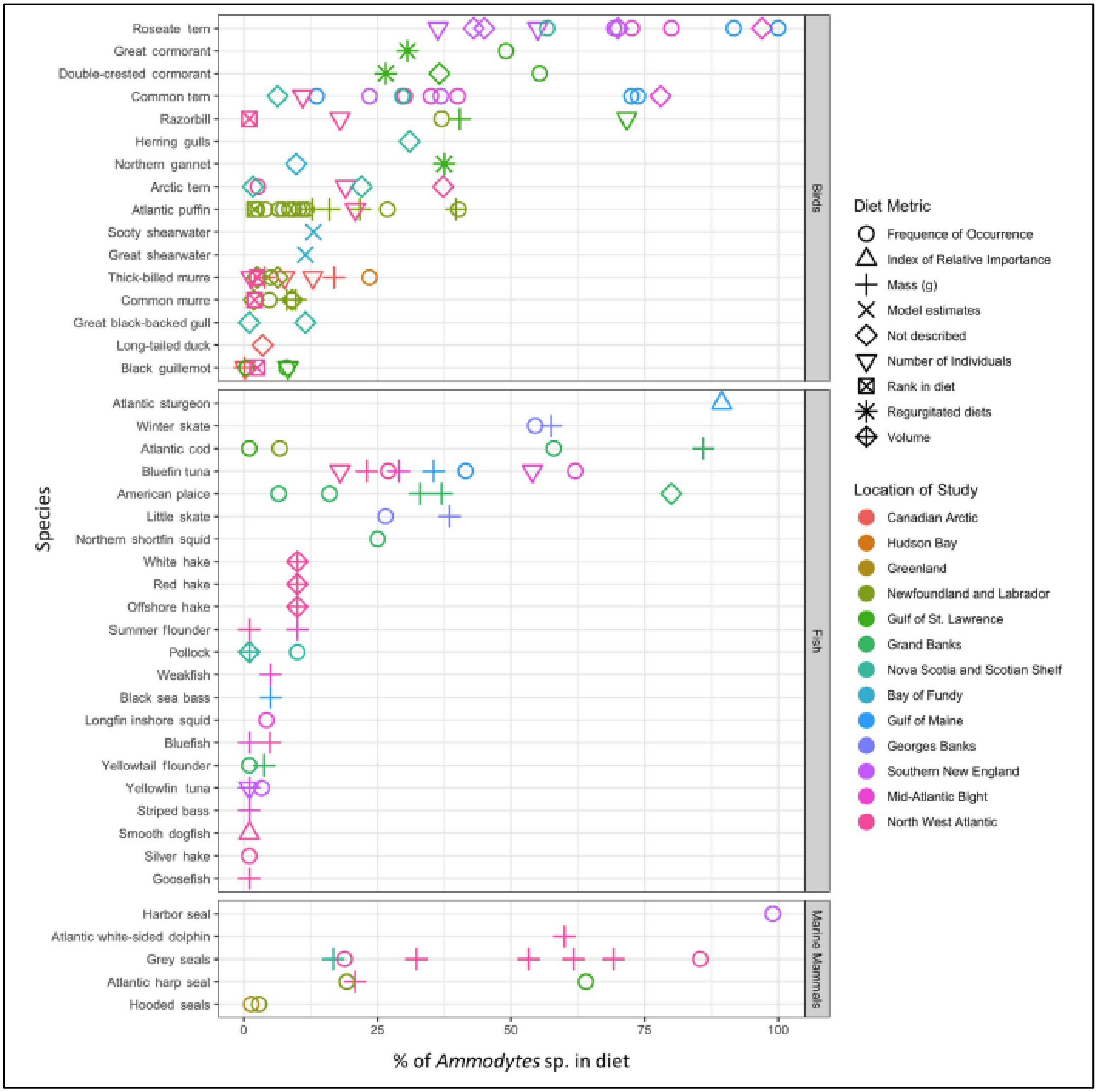


Figure 27. Conceptual overview of decommissioning options for offshore structures (Reproduced with permission from Sommer et al., 2019)

A5: Percentage of sand lance in other species diets

Table 23. Percentage of Ammodytes sp. in diet (Reproduced with permission from Staudinger et al., 2020)



Proportion of the Northwest Atlantic sand lance in seabird, fish, squid and marine mammal diets based on the results of a systematic literature review. Species within each taxonomic group are generally ordered from highest to lowest importance of sand lance in their respective diets. Diet *metrics are indicated as symbols, and study locations are indicated by color (Staudinger et al., 2020).*

A6: Stages and Geoprocessing Tools

First stage: Collection of data from external data sources.

Second stage: An ArcGIS Pro project was created for each attribute and its underlying criterion to make it more tractable i.e. nine projects in total:

- The overall environment settings in ArcGis Pro were first set e.g. Coordinate Systems > Projected Coordinate System: UTM > Europe > ETRS 1989 UTM Zone 32N; Processing Extent: StudyArea[20]; Cell Size: 100; Mask: StudyArea; Cell Alignment: StudyArea.

Geoprocesssing tools - the most used tools for these operations[21] were:

- Extract by Mask – extracting the cells of a raster corresponding to the areas defined by a mask. A subset of sea depth from EMODnet, Bathymetry was first extracted using the StudyArea polygon as a feature mask.
- Clip Raster, Clip (vector) – cutting out a portion of a raster or vector dataset. These tools were used e.g. when clipping the seabed vector data and windspeed rasters after the mosaic process - see below.
- Mosaic To New Raster – merging multiple raster datasets into a new raster dataset. Only portions of windspeed rasters acquired from Global Wind Atlas (data provider) were able to be downloaded at one time. This tool made it possible to merge the different downloads together to cover the whole study area.
- Merge - combining multiple input datasets into a single, new output dataset. This tool can combine point, line or polygon feature classes or tables. For example, the study areas East, West, and Dogger Bank were combined into one dataset (layer). The same tool was used in combining munition (UXO) and shipwrecks, and cables and pipelines.
- Buffer – creating buffer polygons around input features to a specified distance. This tool was used to define buffer zones at 100m around munition and wrecks and 200m around cables and pipelines.
- Feature To Raster – converting features to a raster dataset. Buffered pipelines/cables layer were used as input data to make a rasterized pipeline layer as output data.

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[20] The StudyArea is a shapefile of merged study areas (by author) based on data from Dataforsyningen, DEA (2017), EMODnet Human activities.

[21] Tool descriptions taken from ArcGIS Pro 2.7 Documentation.

- Euclidean Distance – calculating for each cell the Euclidean distance to the closest source. This tool was relevant for calculating and comparing distances to shore (landfall point). It was also used to buffer the planned Vikinge Banke OWF from a point feature data and calculating optimal distances to a potential energy island in the Dogger Bank area.
- Reclassify - reclassifying (or changing) the values in a raster. This tool was used to reclassify raster maps to output raster constraint maps i.e. changing the map values to either one (suitable) or zero (unsuitable) plus reclassifying suitability index (SI) maps into three classes: 'Low Suitability', 'Medium Suitability' and 'High Suitability'.
- Raster Calculator - the constraint maps were all multiplied in the Raster Calculator to generate the composite constraint map and the overall suitability maps for the three different scenarios i.e. by multiplying the composite constraint map with the equal priority SI map, the ecological priority SI map and the economic priority SI map respectively.
- Fuzzy Membership - transforming the input rasters into a 0 to 1 scale, indicating the strength of a membership in a set, based on a specified fuzzification algorithm. A value of 1 indicates full membership in the fuzzy set, with membership decreasing to 0, indicating it is not a member of the fuzzy set. This tool was used to generate the factor maps with fuzzy values.
- Erase Tool - creating feature class by overlaying the input features with the erase features. Only those portions of the input features falling outside the erase features are copied to the output feature class. This tool was used to subtract the planned Vikinge Banke OWF from the Dogger Bank distance raster as the distance raster at the OWF location had a value of one(=suitable) which was incorrect.
- Intersect Tool – computing a geometric intersection of the input features. Features or portions of features that overlap in all layers or feature classes will be written to the output feature class. This tool was used to create the Vikinge Banke OWF polygon in the Dogger Bank area (Intersection between buffered Vikinge Banke OWF and Dogger Bank with a spatial extent of 98 km^2.
- Create Constant Raster (see above). This tool was used to create the planned Vikinge Banke OWF as a polygon raster. The raster was assigned a constant value of zero (=not suitable) and was merged back to the erased planned OWF raster using the Mosaic Tool.

Third stage: Following the pre-processing operations, the generation of result maps was performed. Relevant tools and operations were:
Calculation of weights for the three scenarios in a comparison matrix was performed using MS Excel, MATLAB and PriEst to validate weights and consistency.
Weighted Sum – overlaying several rasters, multiplying each by their given weight (derived from the AHP comparison matrix) and summing them together to generate suitability index (SI) maps

for the equal priority, ecosystem priority and economic priority respectively. This operation is also known as weighted linear combination (WLC).

A7: Individual Constraint Maps

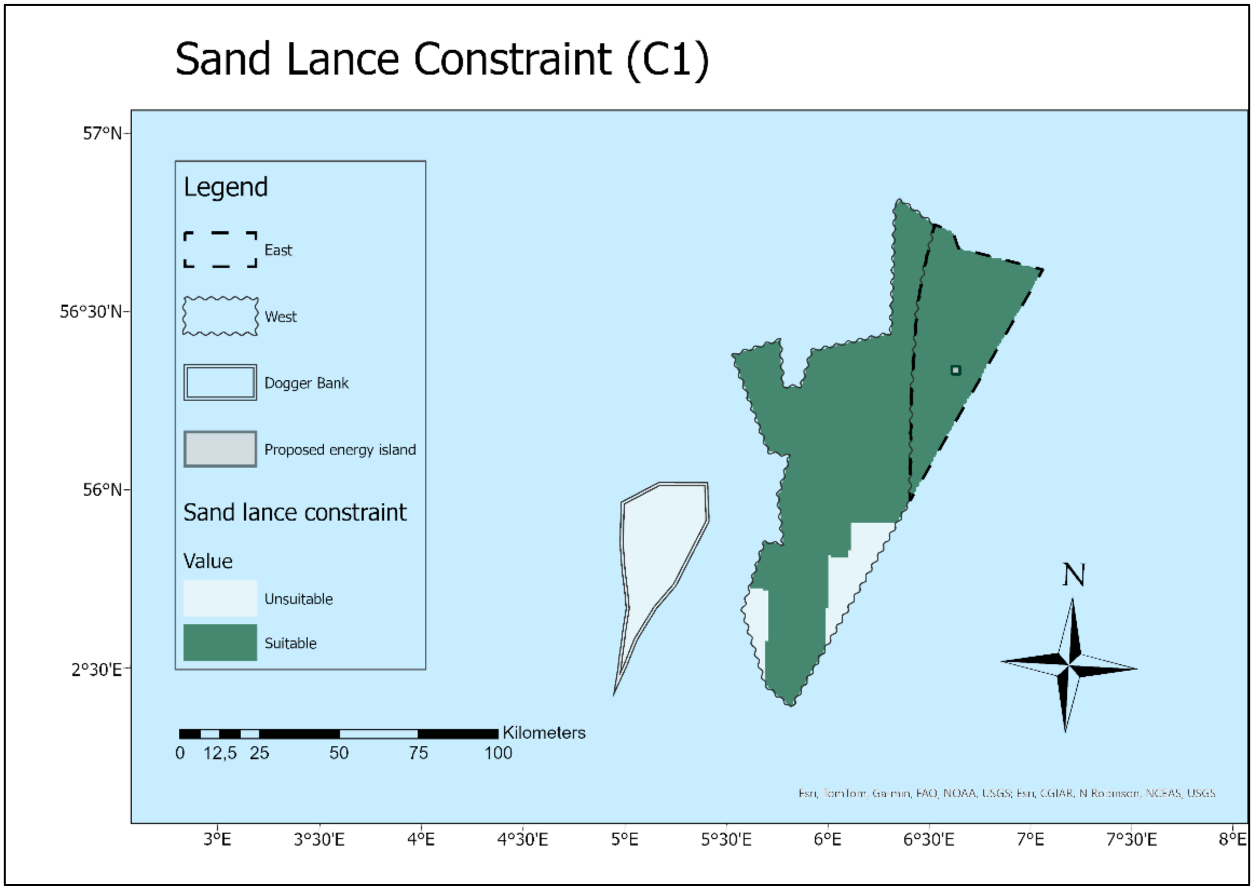

Figure 28. Sand lance constraint map

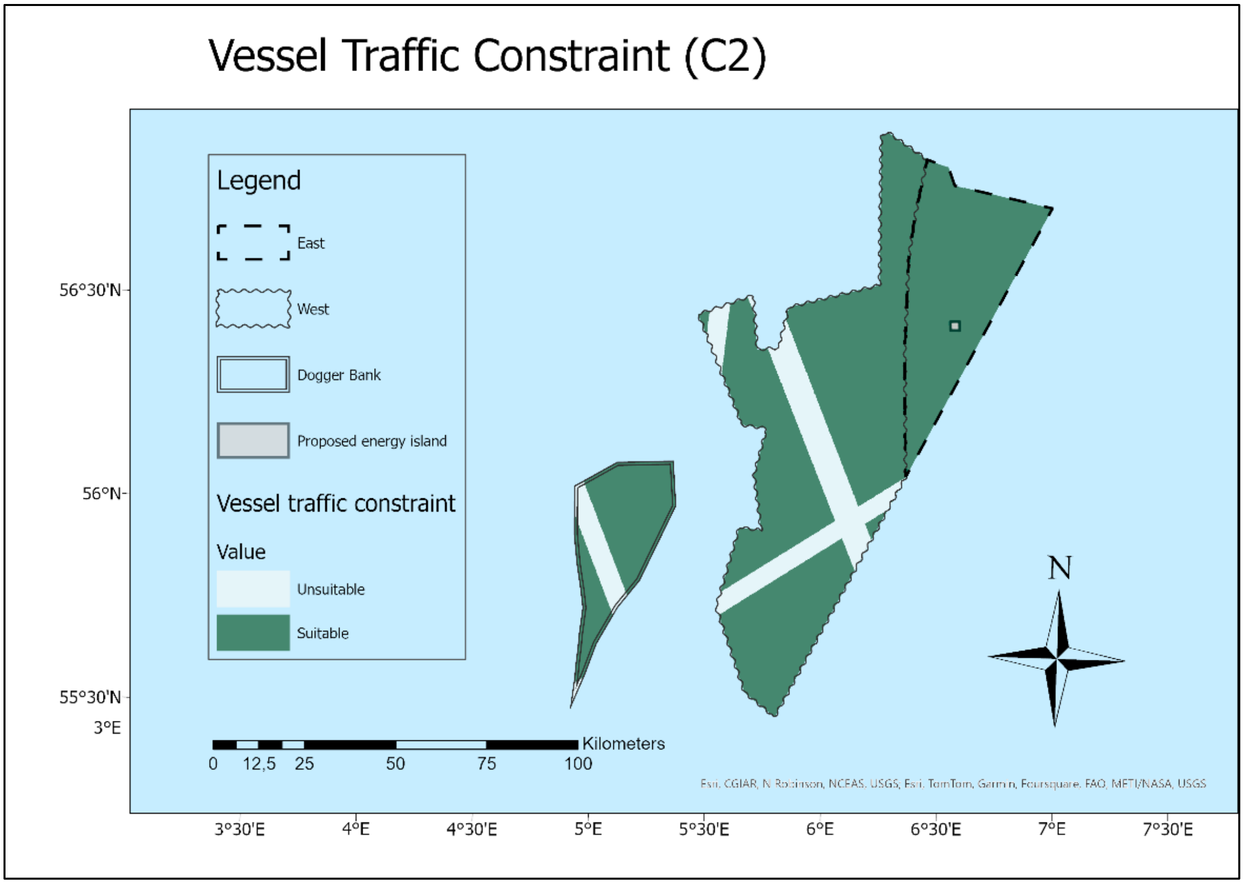

Figure 29. Vessel traffic constraint map

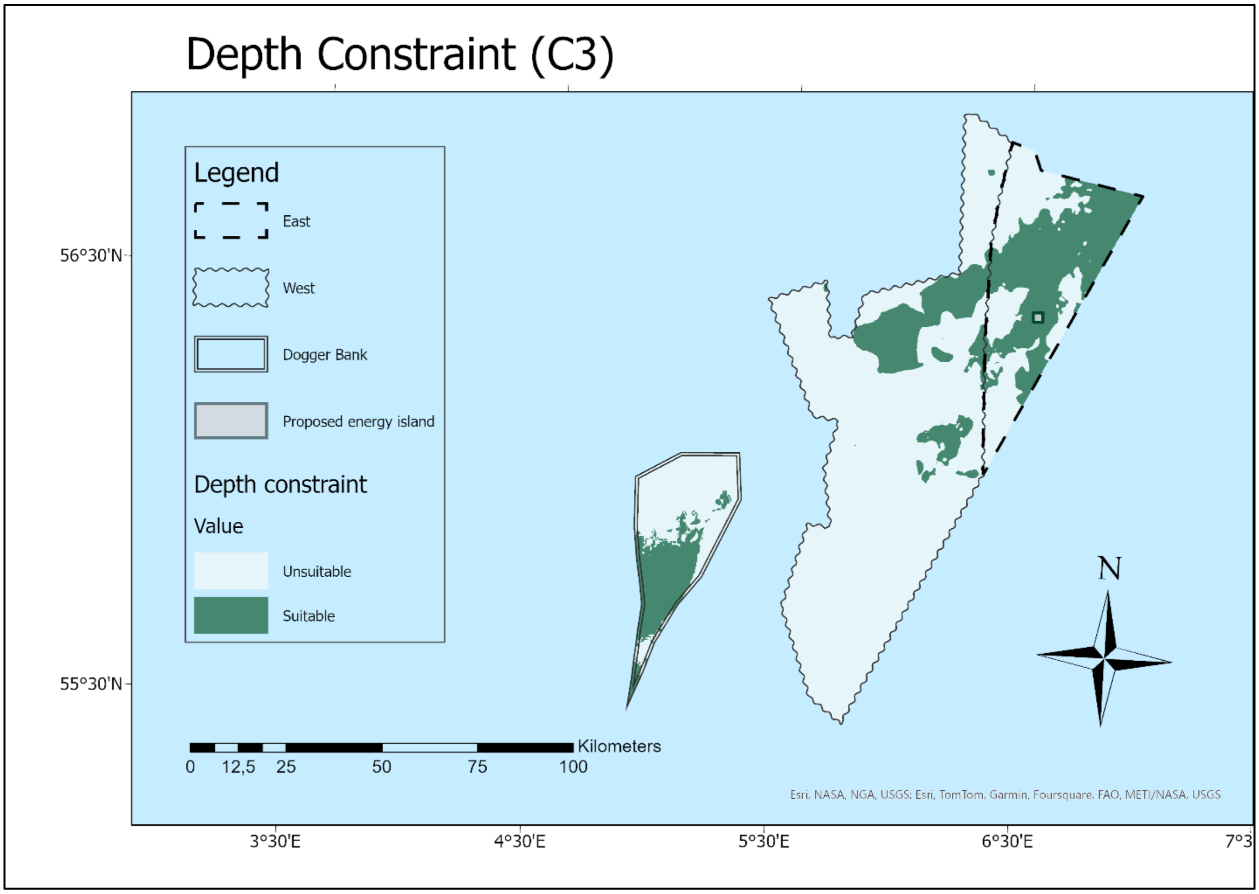

Figure 30. Depth constraint map

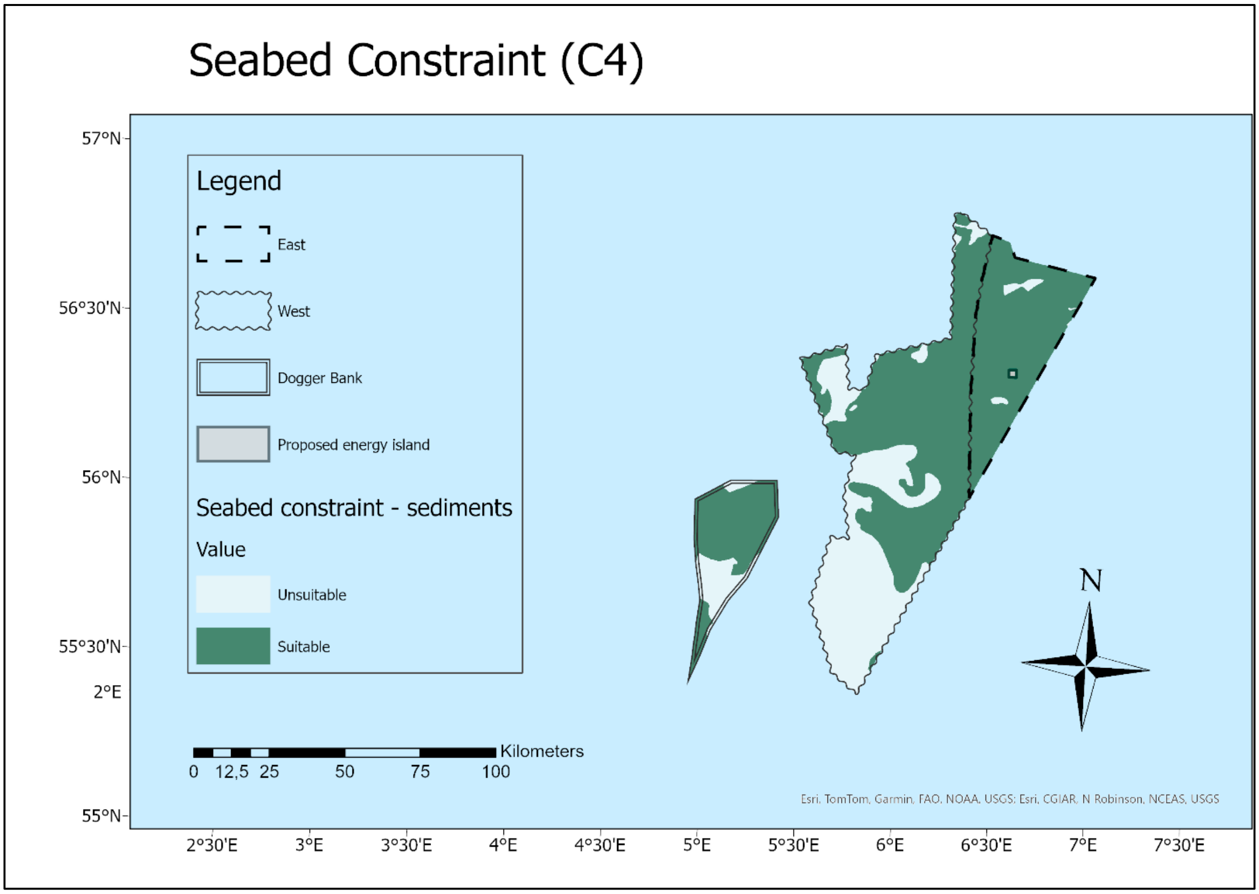

Figure 31. Seabed constraint map

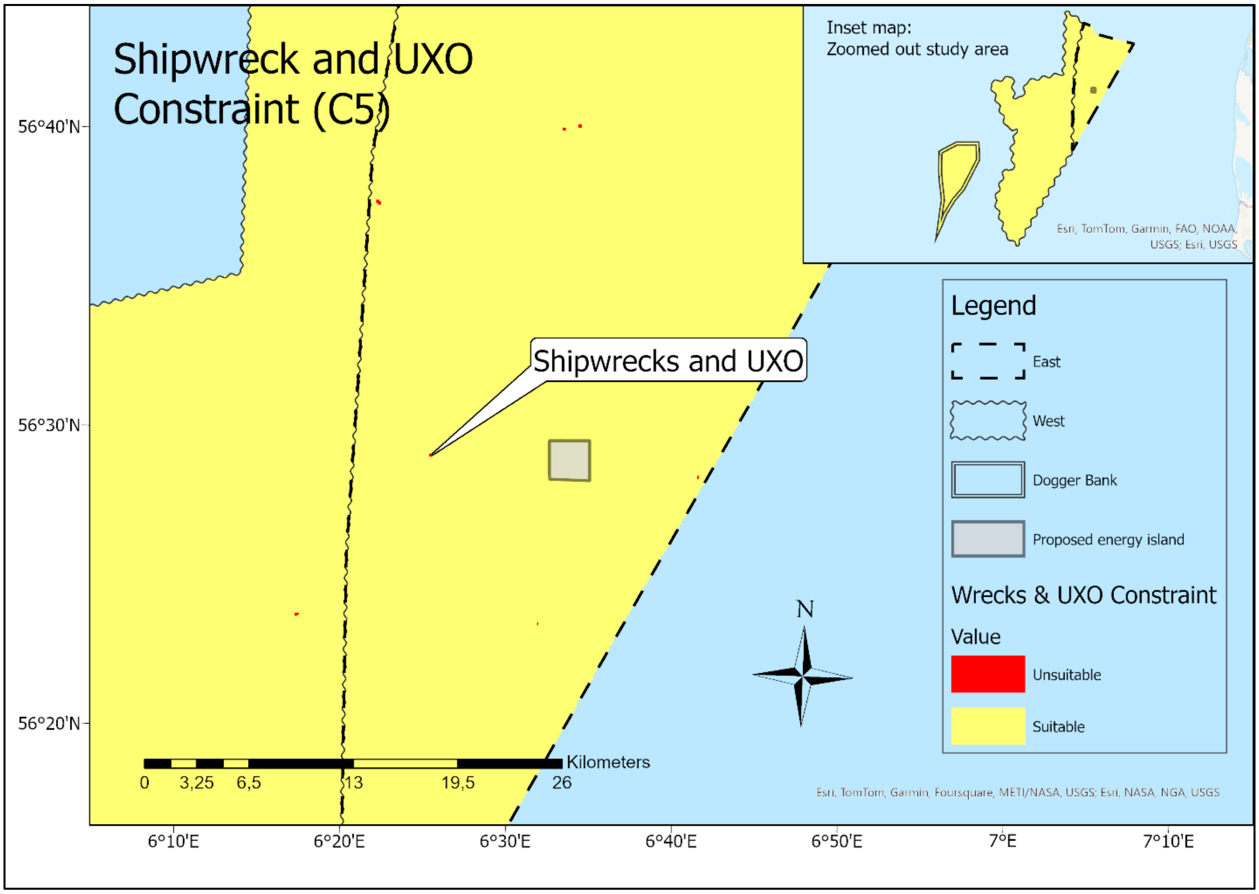

Figure 32. Shipwrecks and UXO constraint map

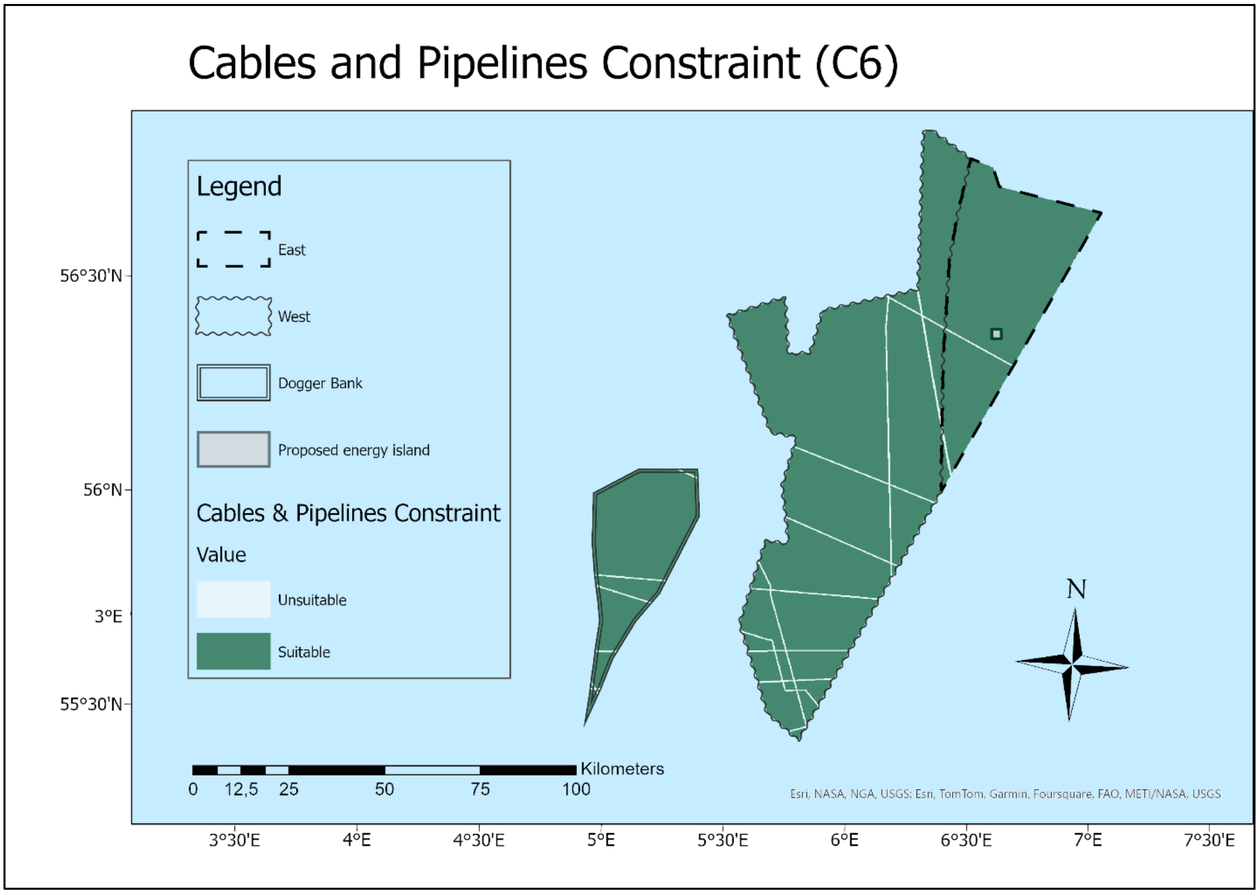

Figure 33. Cables and pipelines constraint map

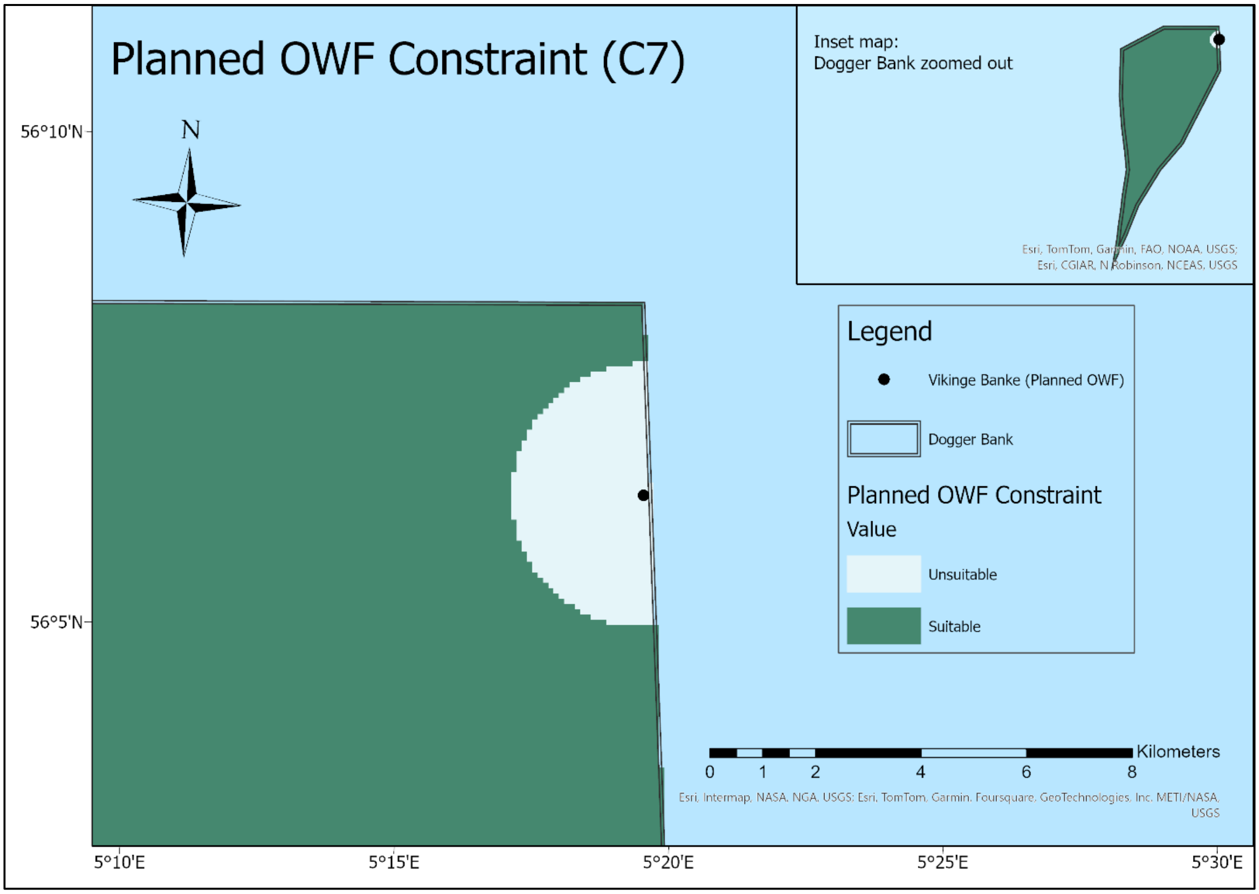

Figure 34. Planned OWF constraint map

A8: Calculation of Weights for Factor Attributes

A8-1: Weights - Ecological Importance Scenario

In step 1, judgement values from Saaty's scale of importance were entered in a comparison matrix (Table 24). In step 2, the values were normalized so that each column total would sum up to one (Table 25). Finally in step 3, the relative weights (eigenvectors) were calculated using the formula: ∑*weights/n,* where *n* is the number of factor attributes – in this case 5.

In other words, all normalized values in each row were added and divided by 5 for every factor (Table 26). The same calculation of eigenvector was performed in MATLAB and PriEst software which resulted in slightly different weight values (Table 27). The MATLAB values were used in the analysis as they were expected to be more accurate.

Step 1:

Table 24. Comparison matrix - ecological importance

Factors	F1	F2	F3	F4	F5
F1 – Sand lance	1	9	4	9	9
F2 - Windspeed	1/9	1	1/4	1	1
F3 - Depth	1/4	4	1	5	5
F4 – Distance	1/9	1	1/5	1	1
F5 - Proximity	1/9	1	1/5	1	1
Sum	**1.583**	**16**	**5.65**	**17**	**17**

Step 2:

Table 25. Normalization of values - ecological

Factors	F1	F2	F3	F4	F5
F1 – Sand lance	0.632	0.562	0.7080	0.529	0.529
F2 - Windspeed	0.070	0.062	0.0442	0.059	0.059
F3 - Depth	0.158	0.250	0.1770	0.294	0.294
F4 – Distance to shore	0.070	0.063	0.0354	0.059	0.059
F5 – Proximity to plan OWF	0.070	0.063	0.0354	0.059	0.059
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

Step 3:

Table 26. Calculation of eigenvector (weights) - ecological

Factors	F1	F2	F3	F4	F5	Weights
F1	0.632	0.562	0.7080	0.529	0.529	0.592
F2	0.070	0.062	0.0442	0.059	0.059	0.059
F3	0.158	0.250	0.1770	0.294	0.294	0.235

F4	0.070	0.063	0.0354	0.059	0.059	0.057
F5	0.070	0.063	0.0354	0.059	0.059	0.057
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

Table 27. Weight calculation in MATLAB and PriEst

Factors	Weights
F1	0.600
F2	0.058
F3	0.230
F4	0.056
F5	0.056
Sum	**1.000**

A8-2: Calculation of Eigenvalue (λ*max*), CI and CR - Ecological

The eigenvalue (λ*max*) which is essential for the consistency calculation was calculated by multiplying each column sum from original matrix in step 1 from the with the respective factor weight from the eigenvector.

In the case of the ecological importance scenario, this was performed as follows:

λmax = (1.583*0.592) + (16*0.059) + (5.65*0.235) + (17*0.057) + (17*0.057) = **5.1501**

The value calculated in MATLAB = **5.0694**

CI = (5.0694 – n) / n-1

CI = 0.0694 / 4 = 0.01735

RI when n = 5: 1.12

CR = CI / RI

CR = 0.01735 / 1.12 = **0.01549**

The judgements were considered acceptable as the CR < 0.10.

A8-3: Weights - Economic Importance Scenario

A similar method was used to calculate the weights in the economic importance scenario, however, with an emphasis on economic factors such as windspeed and distance to shore. The consecutive steps are shown below in Table 28 – 30. The same calculation of eigenvector was performed in MATLAB and PriEst software which resulted in slightly different weight values (Table 31). Since both MATLAB and PriEst software came out with the same results and are expected to be more accurate, their weights were used in the economic importance scenario.

Table 28. Comparison matrix - economic importance

Factors	F1	F2	F3	F4	F5
F1 – Sand lance	1	1/9	1/5	1/9	1/3
F2 - Windspeed	9	1	2	1	5
F3 - Depth	5	1/2	1	1/3	4
F4- Distance to shore	9	1	3	1	5
F5 – Proximity to plan OWF	3	1/5	1/4	1/5	1
Sum	**27**	**2.81**	**6.45**	**2.64**	**15.33**

Table 29. Normalization of values – economic

Factors	F1	F2	F3	F4	F5
F1	0.037	0.040	0.031	0.042	0.022
F2	0.333	0.355	0.310	0.378	0.326
F3	0.185	0.178	0.155	0.126	0.261
F4	0.333	0.356	0.465	0.378	0.326
F5	0.111	0.071	0.039	0.076	0.065
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

Table 30. Calculation of eigenvector (weights) - economic

Factors	F1	F2	F3	F4	F5	Weights
F1	0.037	0.040	0.031	0.042	0.022	0.034
F2	0.333	0.356	0.310	0.378	0.326	0.341

F3	0.185	0.178	0.155	0.126	0.261	0.181
F4	0.333	0.356	0.465	0.378	0.326	0.372
F5	0.111	0.070	0.039	0.076	0.065	0.072
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

Table 31. Weights in MATLAB and PriEst

Factors	**Weights**
F1	0.034
F2	0.339
F3	0.181
F4	0.375
F5	0.071
Sum	**1.000**

A8-4: Calculation of Eigenvalue (λ*max*), CI and CR - Economic

In the case of the economic importance scenario, this was performed as follows:

(27*0.034) + (2.81*0.341) + (6.45*0.181) + (2.64*0.372) + (15.33*0.072) = **5.1441**

The value calculated in MATLAB = **5.1105**

CI = (5.1105 – n) / n-1

CI = 0.1105 / 4 = 0.027625

RI when n = 5: 1.12

CR = CI / RI

CR = 0.0276 / 1.12 = **0.02466** -> The judgements were considered acceptable as the CR < 0.10.

A9: Suitability Index Maps for the Three Scenarios

The equal weights scenario SI map is shown in Figure 35, the ecological importance scenario SI map is shown in Figure 36 and the economic importance scenario SI map is shown in Figure 37 below.

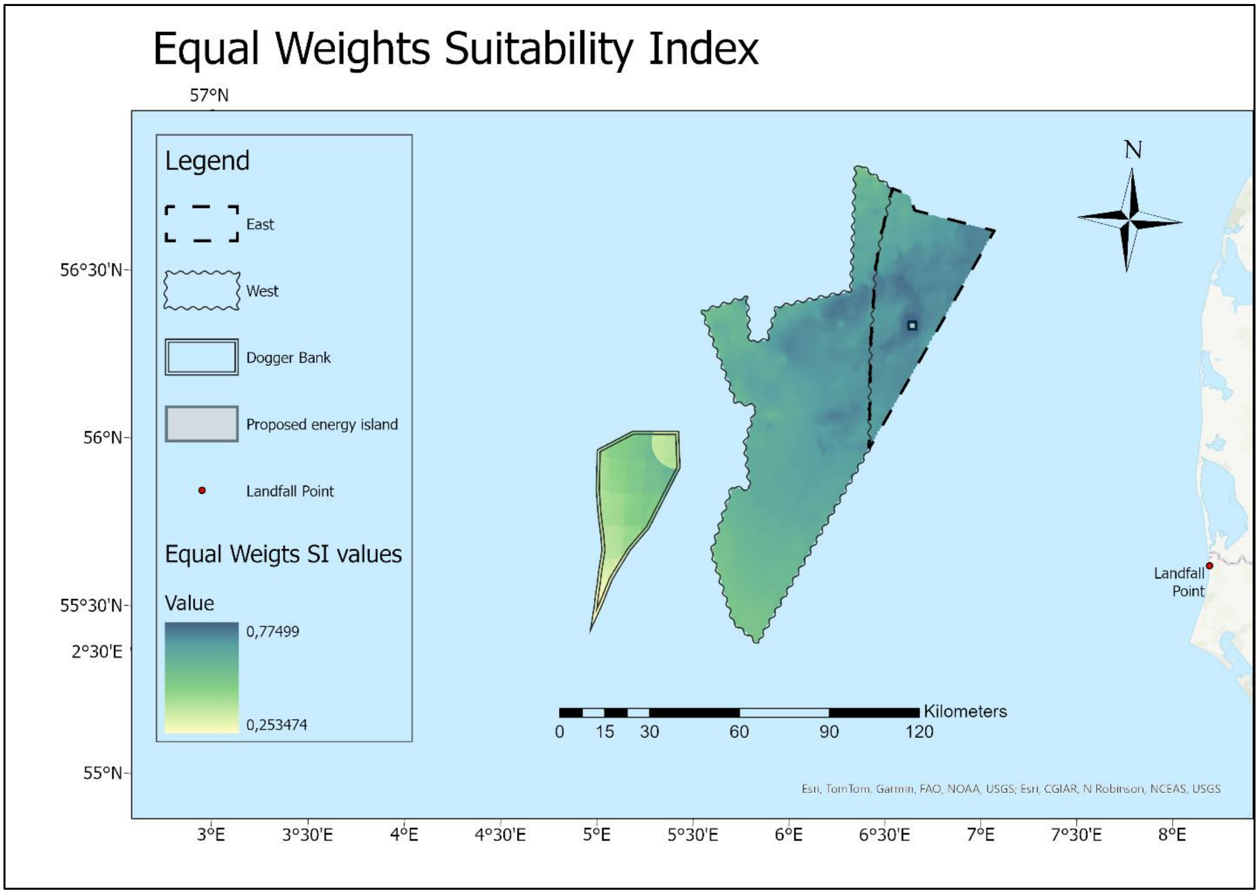

Figure 35. Equal weights scenario SI map

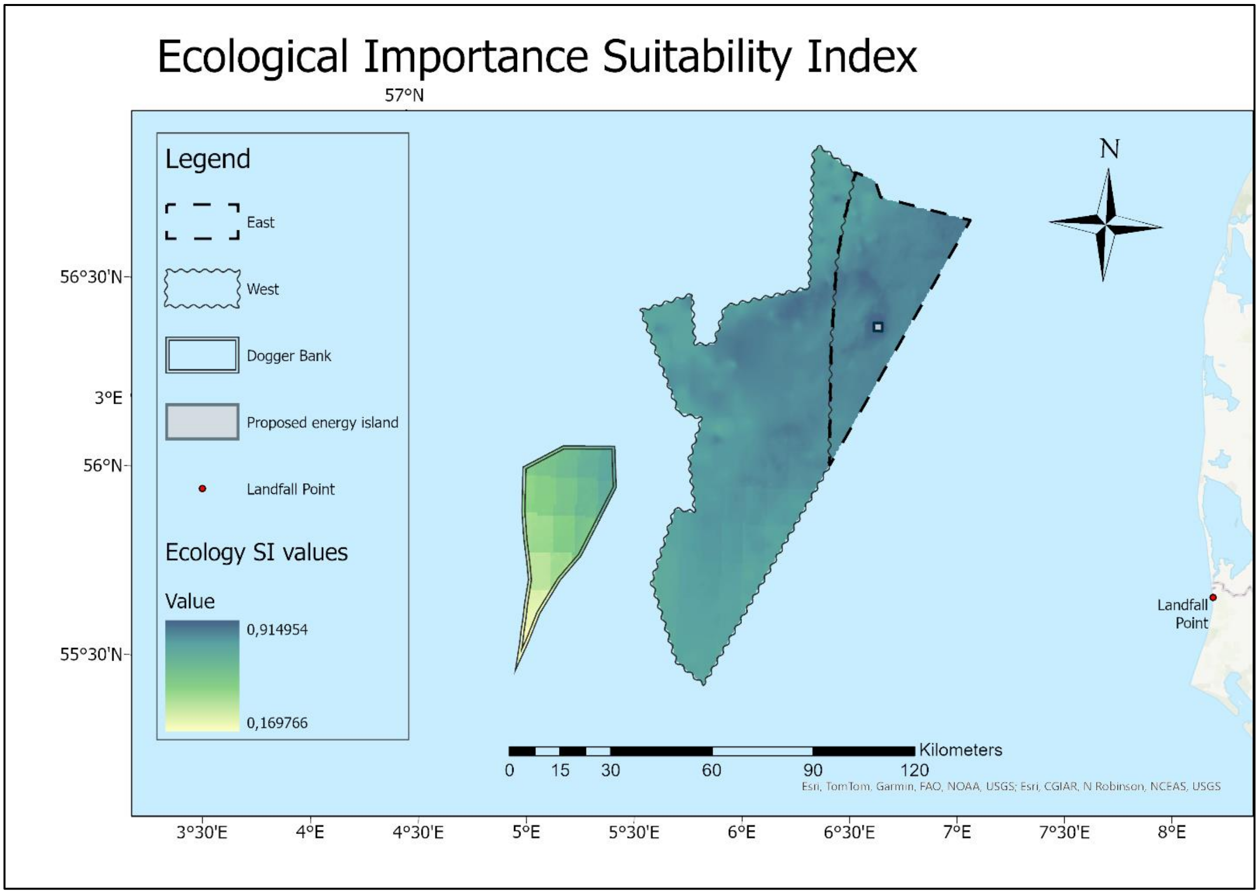

Figure 36. Ecological scenario SI map

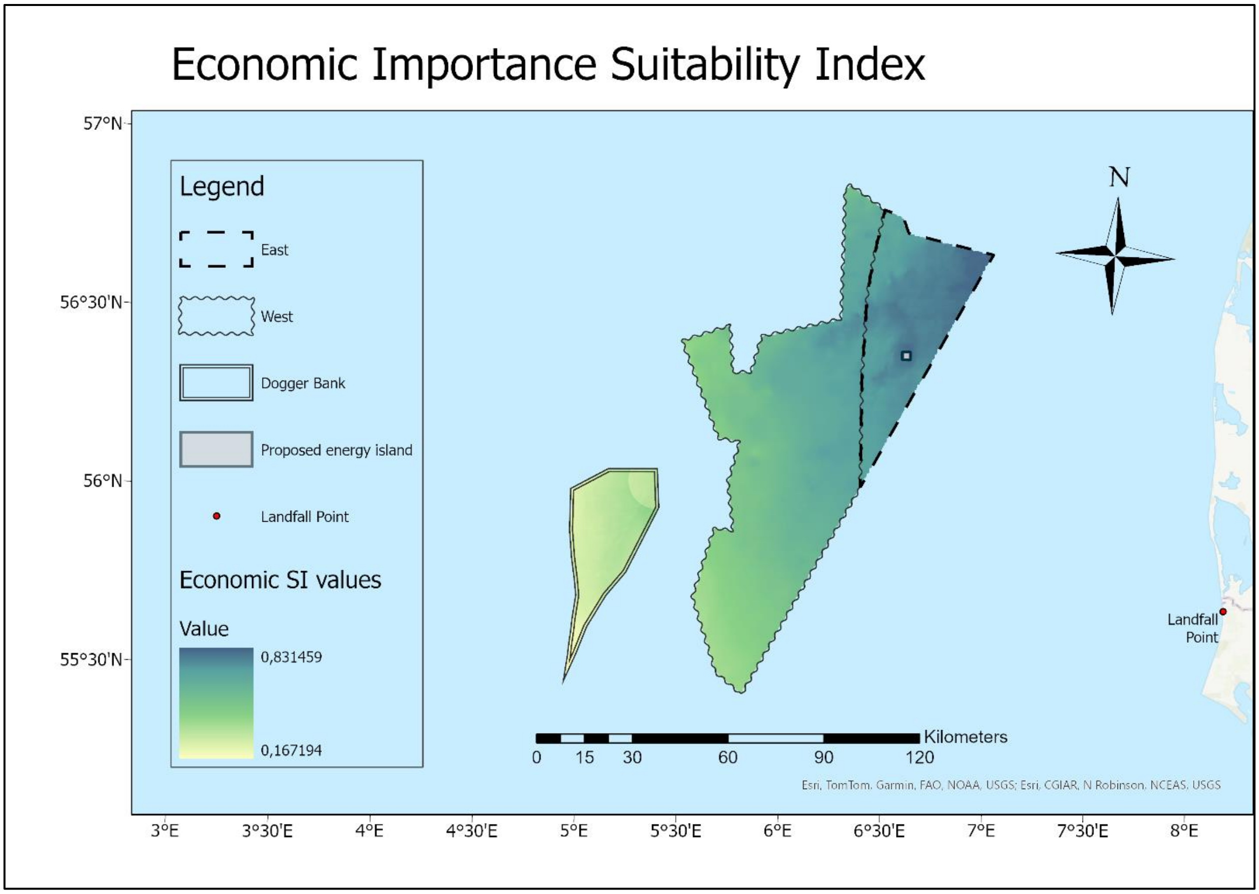

Figure 37. Economic scenario SI map

A10: Calculation of Reclassified SI Maps

Equal importance:

Total number of cells: 700 726.

Number of Cells of 'High Suitability': 3 486 / 700 726 = 0,0049 ≈ **0.5%**

Number of Cells of 'Medium Suitability': 622 553 / 700 726 = 0,8884 ≈ **89%**

Number of Cells of 'Low Suitability': 74 687 / 700 726 = 0.1065 ≈ **11%**

Ecological importance:

Total number of cells: 700 422.

Number of Cells of 'High Suitability': 536 531 / 700 422 = 0.766 ≈ **76.5%**

Number of Cells of 'Medium Suitability': 115 577 / 700 422 = 0.1650 = **16.5%**

Number of Cells of 'Low Suitability': 48 314 / 700 422 = 0,0689 ≈ **7%**

Economic Importance:

Total number of cells: 699 494.

Number of Cells of 'High Suitability': 70 620 / 699 494 = 0.1009 = **10%**

Number of Cells of 'Medium Suitability': 409 405 / 699 494 = 0.585 ≈ **58.5%**
Number of Cells of 'Low Suitability': 220 182/ 699 494 = 0.3147 ≈ **31.5%**

A11: Sensitivity Analyses and Calculation of Weights for the Scenarios

A11-1: Ecological Scenario Weights - Sensitivity Analysis

Table 32. Comparison matrix - sensitivity analysis ecological

Factors	F1	F2	F3	F4	F5
F1 – Sand lance	1	7	3	7	7
F2 - Windspeed	1/7	1	1/3	1	1
F3 - Depth	1/3	3	1	4	4
F4 – Distance to shore	1/7	1	1/4	1	1
F5 – Proximity planned OWF	1/7	1	1/4	1	1
Sum	**1.762**	**13**	**4.83**	**14**	**14**

Table 33. Normalization of values – ecol sensitivity

Factors	F1	F2	F3	F4	F5
F1	0.568	0.538	0.621	0.500	0.500
F2	0.081	0.077	0.069	0.071	0.071
F3	0.189	0.231	0.207	0.286	0.286
F4	0.081	0.077	0.052	0.071	0.071
F5	0.081	0.077	0.052	0.071	0.071
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

Table 34. Calculation of eigenvector ecol - ∑weights/n

Factors	**F1**	**F2**	**F3**	**F4**	**F5**	**Weights**
F1	0.568	0.538	0.620	0.500	0.500	0.545
F2	0.081	0.077	0.069	0.071	0.071	0.074
F3	0.189	0.231	0.207	0.286	0.286	0.240
F4	0.081	0.077	0.052	0.071	0.071	0.071
F5	0.081	0.077	0.052	0.072	0.072	0.070
Sum	1.000	1.000	1.000	1.000	1.000	1.000

A11-2: Calculation of Eigenvalue (λ*max*), CI and CR – Ecological Sensitivity Analysis

The eigenvalue for the ecological scenario sensitivity analysis was calculated to **5.0546** in Excel by the author.

The value calculated in MATLAB = **5.0326**

CI = (5.0326 – n) / n-1

CI = 0.0326 / 4 = 0.00815

RI when n = 5: 1.12

CR = CI / RI

CR = 0.00815 / 1.12 = **0.007** **-**> The judgements were considered acceptable as the CR < 0.10.

A11-3: Validation of Weights in MATLAB and PriEst - Ecological

The same comparison matrix was input in MATLAB and PriEst software to validate the values. The calculated values from MATLAB and PriEst are shown in Table 35. Since both MATLAB and PriEst software came out with almost the same results and the same CR as the author's calculation 0.007 and are expected to be more accurate, their weights were used in the ecological sensitivity analysis. The overall ecological scenario sensitivity analysis map is shown in Fig. 38.

Table 35. Weights in MATLAB and PriEst - ecol

Factors	**Weights**
F1	0.548
F2	0.074
F3	0.238
F4	0.070
F5	0.070
Sum	**1.000**

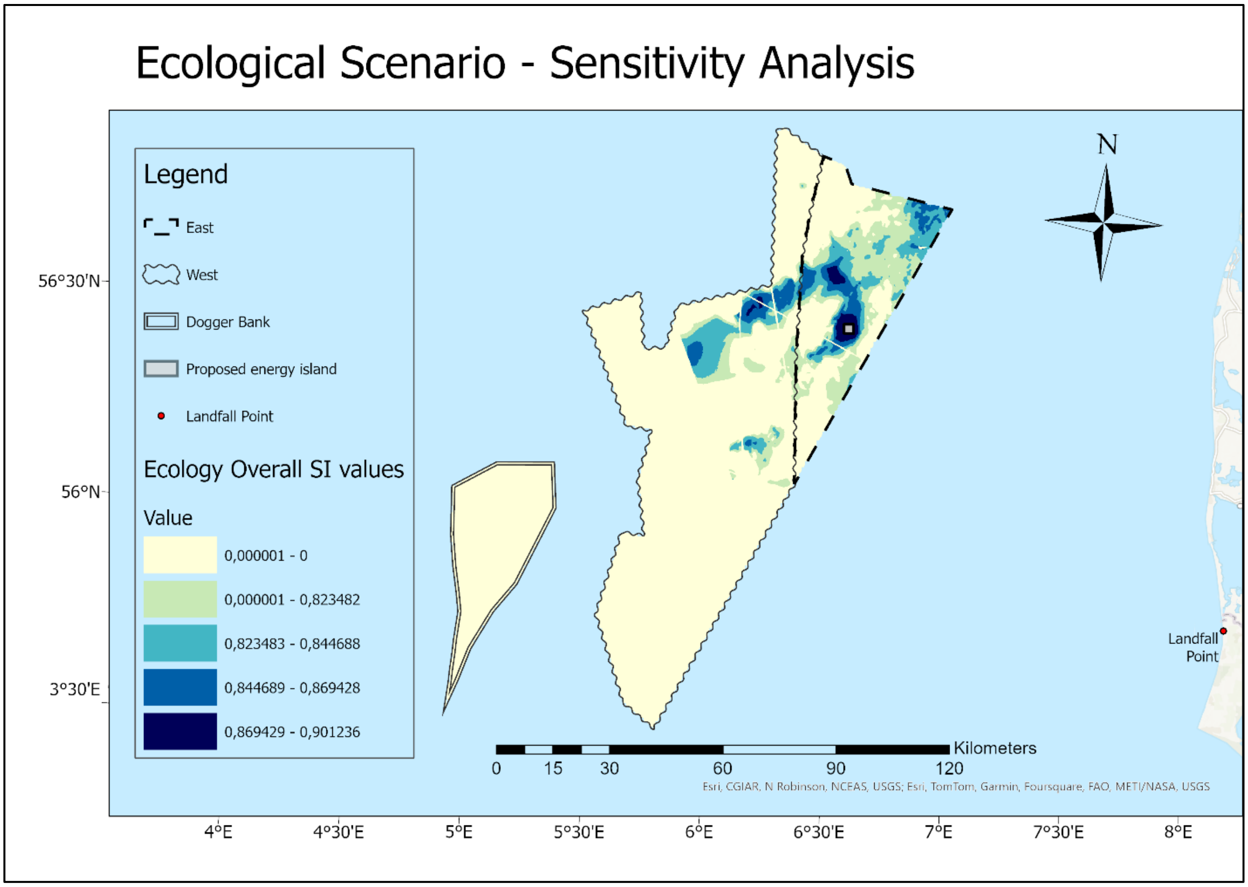

Figure 38. Ecological scenario - sensitivity analysis

A11-4: Economic Scenario Weights – Sensitivity Analysis

Table 36. Comparison matrix - sensitivity analysis economic

Factors	F1	F2	F3	F4	F5
F1 – Sand lance	1	1/7	1/4	1/7	1/2
F2 - Windspeed	7	1	1	1	4
F3 - Depth	4	1	1	1/2	3
F4 – Distance to shore	7	1	2	1	4
F5 – Proximity to planned OWF	2	1/4	1/3	1/4	1
Sum	**21**	**3.39**	**4.58**	**2.89**	**12.5**

Table 37. Normalization of values – econ sensitivity

Factors	F1	F2	F3	F4	F5
F1	0.048	0.042	0.055	0.049	0.040
F2	0.333	0.295	0.218	0.346	0.320
F3	0.191	0.295	0.218	0.173	0.240
F4	0.333	0.295	0.436	0.346	0.320
F5	0.095	0.073	0.073	0.086	0.080
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

Table 38. Calculation of eigenvector - econ ∑weights/n

Factors	F1	F2	F3	F4	F5	Weights
F1	0.048	0.042	0.055	0.049	0.040	0.047
F2	0.333	0.295	0.218	0.346	0.320	0.302
F3	0.191	0.295	0.218	0.173	0.240	0.223
F4	0.333	0.294	0.436	0.346	0.320	0.346
F5	0.095	0.074	0.073	0.086	0.080	0.082
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

A11-5: Calculation of Eigenvalue (λ*max*), CI and CR – Economic Sensitivity Analysis

The eigenvalue for the economic scenario sensitivity analysis was calculated to **5.0512** in Excel by the author.

The value calculated in MATLAB = **5.0507**

CI = (5.0507 – n) / n-1

CI = 0.0507 / 4 = 0.012675

RI when n = 5: 1.12

CR = CI / RI

CR = 0.012675 / 1.12 = **0.011** **-**> The judgements were considered acceptable as the CR < 0.10.

Table 39. Weights in MATLAB and PriEst - econ

Factors	Weights
F1	0.047
F2	0.302
F3	0.224
F4	0.346
F5	0.081
Sum	**1.000**

A11-6: Validation of Weights in MATLAB and PriEst - Economic

Since both MATLAB and PriEst software came out with the same results and same CR as the author's calculation 0.011 the weights were applied in WLC operation in the sensitivity analysis. The overall economic scenario sensitivity analysis map is shown in Fig. 39.

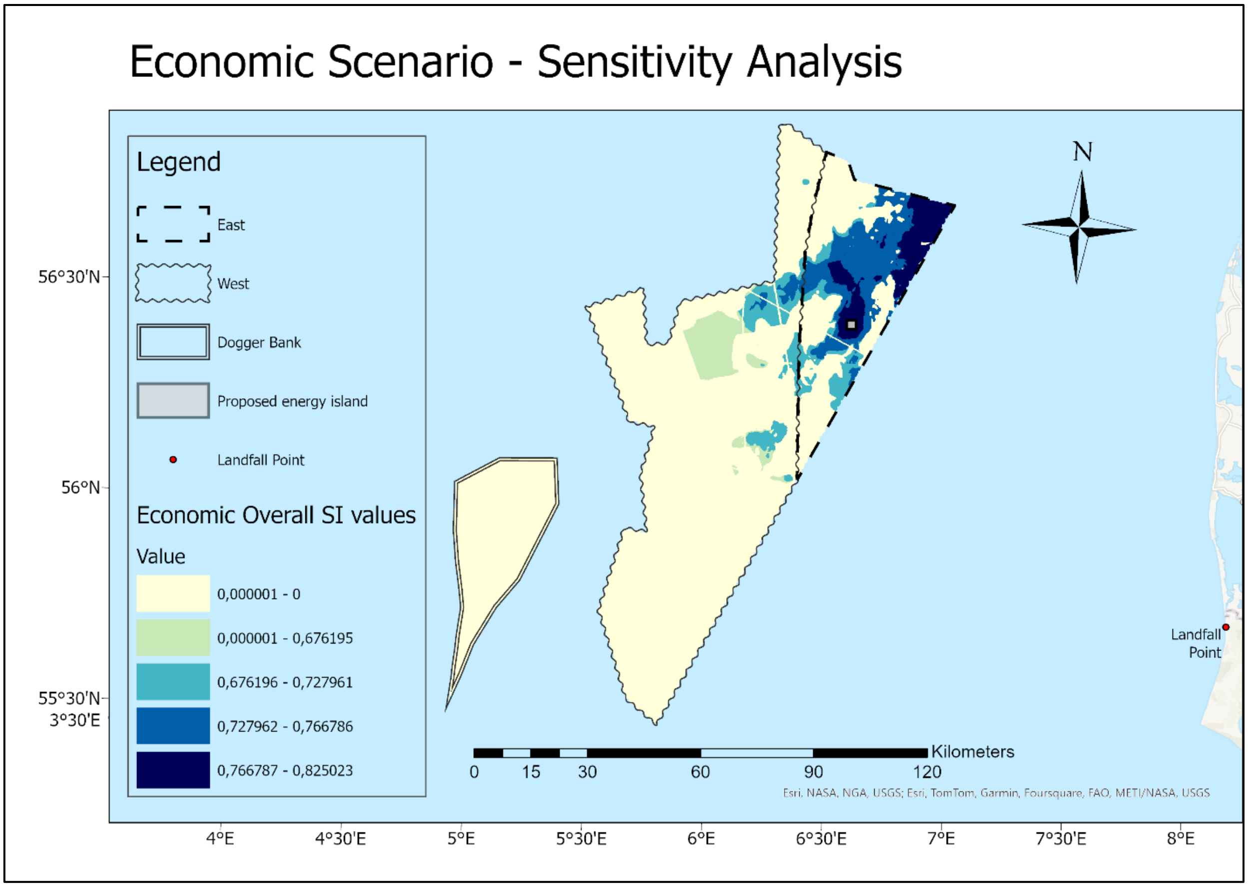

Figure 39. Economic scenario - sensitivity analysis

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