The Effects on Subsurface Marine Biodiversity from Offshore Wind Power Plants

Exploring Mitigation Measures and Enhancement of Biodiversity through Nature Inclusive Design

by Hanna Lundgren & Emma Thoresson

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Supervisor: Max Åhman

Examiner: Jamil Khan

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Supervisor at the Division of Environmental and Energy Systems Studies was Max Åhman.

Examiner at Lund University was Jamil Khan.

Division of Environmental and Energy Systems Studies
Department of Technology and Society
Faculty of Engineering
Lund University

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Preface

This master thesis has been written during the spring of 2024 as the final project of our Master of Science degree in Environmental Engineering. This master thesis has been conducted at the Division of Environmental and Energy System Studies, Faculty of Engineering, Lund University and in collaboration with Eolus Vind AB.

First and foremost, we would like to thank Eolus for the opportunity of writing our master thesis with you. All employees have made us feel welcome and provided us with insights from the wind power industry. We hope this master thesis is in line with your sustainability strategy and constitutes a small contribution to the aim of net positive impact on biodiversity. We want to express our gratitude towards our supervisor Marika Carlsson at Eolus for her excitement and valuable feedback throughout the process.

We would also like to thank our supervisor Max Åhman at LTH, for his support and valuable advice, and our examiner Jamil Khan for providing constructive feedback. Finally, we want to thank all interviewees whose valuable knowledge and insightful perspectives contributed greatly to our master thesis.

Abstract

The demand for renewable energy is extensive while biodiversity is reclining with unprecedented rates of species and habitat loss. Offshore wind power provides renewable energy while also affecting local marine biodiversity – negatively and positively. The offshore wind power plants contribute to effects such as underwater noise, resuspension and settling of sediment, seabed habitat loss, reef effect caused by introduced hard substrate, indirect effects and cumulative effects. Common measures to minimise the negative effects include for example bubble curtains for noise reduction. To achieve a net positive effect on biodiversity, the reef effect can be enhanced by design of foundation and scour protection as well as through Nature Inclusive Design. Nature Inclusive Design is a collective term that includes structures aimed to contribute with habitat for species and ecosystems. The measures were applied on a case study of a planned offshore wind power project, owned by Eolus. The measures to enhance biodiversity were presented in different layouts. Representatives from the County Administrative Board were interviewed to gather opinions on how Nature Inclusive Design affects the permitting process. A wind power project must be admissible by itself, but the implementation of Nature Inclusive Design in wind power projects could lead to potential advantages in the permitting process if the long-term positive effects are established. It is important to consider the local conditions and the target species in an area in order for the enhancement measures to be effective. By utilising the proposed measures to minimise negative effects and enhance positive effects, a balance regarding renewable energy and enhancement of local biodiversity can be established.

Keywords: *Biodiversity, Offshore wind power, Mitigation hierarchy, Nature Positive, Environmental Impact, Nature Inclusive Design, Permitting process.*

Sammanfattning

Efterfrågan på förnybar energi är stor och samtidigt minskar den biologiska mångfalden i en aldrig tidigare skådad takt, med förlust av arter och livsmiljöer. Havsbaserad vindkraft ger förnybar energi och påverkar samtidigt lokal marin biologisk mångfald – negativt och positivt. Havsbaserade vindkraftsparker bidrar till effekter såsom undervattensbuller, resuspension och pålagring av sediment, förlust av livsmiljöer på havsbotten, reveffekt till följd av införande av hårda substrat, indirekta effekter och kumulativa effekter. Åtgärder för att minimera de negativa effekterna inkluderar bland annat bubbelridåer för bullerreducering. För att uppnå en positiv nettoeffekt på den biologiska mångfalden kan reveffekten förstärkas genom utformning av vindkraftsfundament och erosionsskydd samt med naturinkluderande design (*Nature Inclusive Design*). Naturinkluderande design är ett samlingsbegrepp som innefattar strukturer som syftar till att bidra med livsmiljöer för arter och ekosystem. Dessa åtgärder tillämpades på en fallstudie av ett planerat havsbaserat vindkraftsprojekt, ägt av Eolus. Åtgärderna för att förbättra den biologiska mångfalden presenterades i olika layouter. Representanter från Länsstyrelsen intervjuades för att samla in synpunkter kring hur naturinkluderande design påverkar tillståndsprocessen. Ett vindkraftsprojekt måste vara tillåtligt i sig, men implementeringen av naturinkluderande design i vindkraftsprojekt kan potentiellt leda till fördelar i tillståndsprocessen om långsiktiga positiva effekter fastställs. Det har också konstaterats att hänsyn till lokala förhållanden och målarterna i ett område är mycket viktigt för att förbättringsåtgärderna ska bli effektiva. Genom att utnyttja de föreslagna åtgärderna för att minimera negativa effekter och förstärka positiva effekter kan en balans uppnås mellan förnybar energi och främjande av lokal biologisk mångfald.

Acronyms

CAB County Administrative Board.

EIA Environmental Impact Assessment.

GU Unitiversity of Gothenburg.

HELCOM Baltic Marine Environment Protection Commission.

LEC Land and Environment Court.

NID Nature Inclusive Design.

OSPAR Oslo and Paris Convention.

SwAM Swedish Agency for Marine and Water Management.

Contents

1. Introduction

Climate change is a rapidly increasing challenge and a transition of the energy system to renewable energy sources is one of the mitigation strategies to ensure a sustainable future (IPCC 2023). Offshore wind power is one of the emerging renewable energy sources with great potential to generate large quantities of energy (IRENA 2019) that are necessary for Sweden to be able to reach its targets with net zero greenhouse emissions to 2045 (Sveriges Miljömål 2023). During recent years, the offshore wind power industry has grown rapidly, having 34 GW of total installed capacity in Europe until 2023. There was 3.8 GW of new installed offshore capacity during 2023 in Europe. The prediction for new installed offshore capacity from 2024–2030 is 87 GW (Wind Europe 2024). The investment costs have decreased in line with the technical development (Energiforsk 2021) and the proportion of offshore wind power have increased considerably, mainly in Europe and Asia (Energimyndigheten 2023). At the same time, biodiversity loss is a major issue that have risen during recent years, with consequences such as habitat loss and increased numbers of endangered species. A rich biodiversity is necessary for the natural mechanisms and for the ecosystem services to function properly (Secretariat of the Convention on Biological Diversity 2020).

Offshore wind power affects different parts of the environment, both in a positive and negative way. In prior research, Bergström et al. (2022) have identified multiple ways in which the establishment of an offshore wind power plant affects the marine biodiversity in an area. Multiple categories of marine life get affected differently depending on the local conditions, for example marine mammals, fish, seabirds and benthic fauna. The various effects such as underwater noise, seabed habitat loss, resuspension and settling of sediment and the reef effect caused by the introduction of hard substrates arise during the life cycle phases of the wind power plant, in different ways and to different extent (Bergström et al. 2022). It has also been established that different types of foundations affect the biodiversity in different ways (Hammar, S. Andersson, and Rosenberg 2008).

Underwater noise, amongst other effects, occurs during the installation phase in varying levels. Increased ship traffic occurs regardless while dredging and piling takes place depending on the type of foundation. Growth and reef formation can occur on the foundations during the operational phase, which can enhance the local biodiversity (Hammar, S. Andersson, and Rosenberg 2008). The decommissioning phase is less explored since most existing wind power plants have not reached their full life span yet. How the decommissioning is handled and how the marine life is affected depends on what type of foundation that have been used. Short term effects that can emerge include underwater noise and resuspension and settling of sediment. If the foundation is removed completely this is one of the considerable impact factors since the artificial reefs will disappear (Bergström et al. 2022). If the environmental effects to leave the foundations proves more favourable, they will probably be left on the seabed.

There are many types of measures that are being implemented in projects today in order to minimise the negative effects that offshore wind power has on biodiversity (Bergström et al. 2022). Despite this, not more than the necessary precautions are taken. This master thesis will explore the possibilities to utilize the offshore wind power plant area to enhance the local biodiversity to create positive effects on biodiversity. Design aspects and technical choices regarding foundations and scour protections that can be made to create positive effects on biodiversity will be investigated. How Nature Inclusive Design (NID) can be implemented to enhance the local biodiversity will also be explored. NID is a term including measures and solutions that are designed to enhance the habitats for species and ecosystems by adding structures and designing them in a specific way.

The interest in offshore wind power has increased substantially in recent years (Energimyndigheten 2023). The advantages with offshore wind power, in comparison to land based wind power, are stronger and more even winds at sea as well as potential to use larger turbines (Energimyndigheten 2023). When the technical development expands further, larger wind turbines and wind power plants are predicted to be built (Bergström et al. 2022). Today, the largest installed turbines have a capacity of 16 MW (Blain 2023), but turbines of 25 MW or even larger are being predicted for the future (Bergström et al. 2022). Thus, with larger wind turbines and wind power plants, there are further risks that have not yet been considered. Cumulative, larger and previously unpredicted effects could occur. Also, because of the technical development, wind power plants with bottom fixed foundations are able to be established in deeper waters, now over 40 metres (Bergström et al. 2022). This could indicate that new types of areas with other conditions than before will be utilized and exploited, with a risk of new unpredicted effects. Additionally, there are many different interest groups that compete with offshore areas. This means that it can be a further challenge to find suitable places for energy extraction.

The application process in Sweden for establishing an offshore wind power plant is time-consuming and complicated (Berg 2023). How is biodiversity valued in the permitting process, and can positive effects on biodiversity contribute to an advantage? In some other countries such as Denmark and Germany, the procurement of suitable areas looks different than in Sweden. The government points out a suitable area, and there is an auction for the interested actors (Vanhainen 2021). This system could be suitable for including measures for enhancement of biodiversity even more, which will be investigated in this master thesis.

There is knowledge of how offshore wind power plants affect biodiversity but the long-term effects are unknown. The effects from wind power plants on the large scale that are being planned today have potential cumulative effects that are hard to predict. This master thesis will compile information of how biodiversity is affected and what measures and design choices that can be made to minimize negative effects and enhance positive effects. The intention is that the results can be used as a guidance when performing detailed design of offshore wind power plants. The thesis will contribute with knowledge of how the measures to enhance biodiversity affects, and potentially benefits, the permitting process. It is important to find a balance between the advantages with more renewable energy and to promote biodiversity. With planning, technical solutions and well-thought-out design, the ambition is that climate change mitigation and biodiversity enhancement can coexist.

1.1 Aim

The aim of this master thesis is to analyse, from a life cycle perspective, how the negative effects on biodiversity from wind power plants can be minimised, and how its positive effects on biodiversity can be enhanced. Additionally, the aim is to examine what role biodiversity plays in the permitting process and if enhancement of biodiversity can favour the permitting process today or in the future.

1.2 Research Questions

This master thesis will investigate and answer the following questions:

- How is marine biodiversity affected by offshore wind power plants?
- How can design aspects and technical choices for wind power plants minimise negative effects and enhance positive effects on biodiversity?
- How is biodiversity dealt with in the permitting process, and how can measures to enhance biodiversity favour the permitting process?

1.3 Structure

The following chapter contains necessary theory about the definition of biodiversity and the mitigation hierarchy. Then, the method and approach with its limitations is presented. Further, there is background information about the basics of a wind power turbine, the phases of a wind power plant life cycle and different types of foundations. Additionally, information about marine spatial planning and the permitting process are presented. The main part of the thesis contains information about how wind power affects biodiversity from different effect categories and what measures that can be implemented to minimize negative effects and enhance positive effects. Thereafter, this information is applied to a case study where a project is presented, and relevant measures are proposed. Finally, the results from the interview study are analysed which includes how enhancement of positive effects on biodiversity can affect the permitting process, coexistence with the fishing industry and future prospects. The thesis is concluded by a discussion and final conclusions.

2. Biodiversity

There is no general definition of biodiversity that is widely used and well described but many similar versions of definitions exist, although there is a need for an international definition. The term biodiversity can be described using different levels such as genetic diversity, species diversity and ecosystem diversity, which all are important in different ways (Swingland 2013). One of the more widely used definition of biodiversity or biological diversity is from the Convention of Biological Diversity and reads as follows:

> *Biological diversity* means the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems. (Secretariat of the Convention of Biological Diversity 2011)

Biodiversity contributes to providing ecosystem services that are related to human well-being. Such services include provisioning, regulating, cultural and supporting. In the last decades, humans have contributed to extensive species and habitat loss, endangering the ecosystem services that we rely on for our well-being (Millennium Ecosystem Assessment 2005). The pressures that drive this major loss of biodiversity are increasing (Secretariat of the Convention on Biological Diversity 2020). The direct drivers include climate change, land use change, pollution, harvesting, invasive species, and disturbance. At a global scale, climate change is the most important driver. Regarding marine biodiversity, climate change leads to ocean warming as well as sea level rise which are some of the direct drivers of change. The human-mediated drivers are mainly fishing activities but also coastal developments (IPBES 2019). Conservation of biodiversity is crucial for meeting many of the Sustainable Development Goals and also for the Paris Agreement, as many of the solutions are based on natural resources (Secretariat of the Convention on Biological Diversity 2020).

Humans value various kinds of species and ecosystem services in different ways depending on personal preferences. This will affect how a change of species composition is viewed, if it is classified as a positive or negative change (Bergström et al. 2022). When people care about biodiversity, it creates an economic value. People generally care about certain ecosystem functions if it benefits them, but usually certain species are cared for more than the whole ecosystem (Hanley and Perrings 2019). The willingness to pay for something is also increased when the specific species are cute or charismatic (Di Minin et al. 2013). Different ecosystem services are connected to certain ecosystem functions, which are dependent on species that are categorized in trophic levels. The trophic levels affect each other in an ecosystem (Baulaz et al. 2023).

There are different organisations that work with biodiversity and compile lists of threatened species and habitats. The Oslo and Paris Convention (OSPAR) commission works to protect the marine environment of the north-east Atlantic. It consists of fifteen countries' governments together with the EU (OSPAR n.d). Baltic Marine Environment Protection Commission (HELCOM), care for the marine life in the Baltic sea (HELCOM n.d). EU has a strategy for biodiversity for 2030 which have the target that Europe's biodiversity should be on route to recovery by 2030. One of the targets is that 30 percent of the marine areas in Europe should be protected until 2030 (EUR-LEX 2020). The council directive (92/43/EEG) on conservation of natural habitats and of wild fauna and flora has the objective to promote biodiversity. Species as well as habitats have different protection classifications depending on their conservation status.

The directive also includes the creation of Natura 2000 areas, a connected network of protected areas in Europe with specific conservation targets (EUR-LEX 1992).

2.1 Defining the marine biodiversity scope

The relevant species and habitats that are subject to protection and conservation are defined by organisations such as mentioned in the previous section. In Environmental Impact Assessment (EIA) applications for offshore wind power, marine biodiversity is described at group level, for example seabirds, fish, and marine mammals. It can also be described on species level, especially if there are species in the area that are more important, such as a threatened species. In that case more investigations or descriptions concerning the specific species can be included (Koehler 2024, SLU Aqua). Additionally, local conditions dictate which species and habitats are present it the area and important to consider.

As has been identified in EIA reports, some typical species groups in Nordic marine ecosystems are benthic fauna and vegetation, filter feeders, crustaceans, fish and marine mammals. These can be divided into different trophic levels, which can be seen in figure 2.1 below. The whole marine ecosystem is affected by changes in the different trophic levels. The information regarding the trophic levels is from Baulaz et al. (2023). The fifth trophic level includes mammals as top predators such as seal and harbour porpoises. The fourth trophic level are the tertiary consumers consisting of piscivorous fish such as the Atlantic cod. The third trophic level, the secondary consumers, includes smaller fish such as Atlantic herring and European sprat and invertebrates, for example crustaceans such as crabs, lobster and shrimp. The second trophic level, the primary consumers, includes zoo plankton, phytoplankton, filter feeders such as mussels and macroalgae. The first trophic level consists of detritus which include particulate organic matter, dissolved organic matter and suspended nutrients. These trophic levels are also connected to different ecosystem services relevant for different areas.

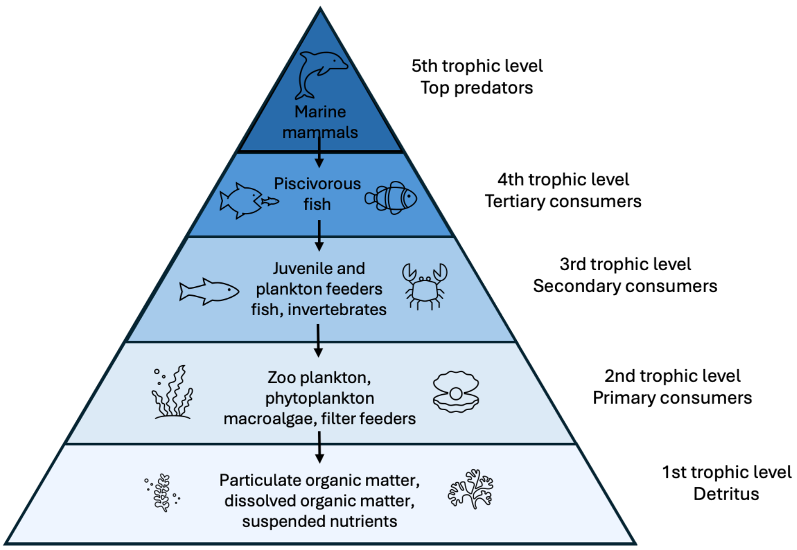

Figure 2.1: The different trophic levels in the ocean eocosystem adapted from Baulaz et al. (2023).

In this master thesis, the focus is on marine subsurface biodiversity which includes everything that lives in the ecosystems of the ocean. The focus will be only on species living under the surface, which means seabirds and bats are excluded. The definition of biodiversity used in this master thesis is the diversity within and between species. Which species that are valued is dependent on the local conditions and the threats and challenges that this specific ecosystem faces.

Biodiversity can also be discussed on a system level, looking at populations over a larger geographical area. A lot of coastal development and construction of wind power can contribute to previously unforeseen cumulative effects. These can affect populations and whole environments on a larger level, highlighting the importance of investigating potential cumulative effects in the EIA applications. Cumulative effects on biodiversity will also be discussed in this master thesis.

2.2 Mitigation hierarchy

In the general rules of consideration in the Swedish Environmental Code (SFS 1998:808), 2 c. 3§, it is stated that the operator should take the necessary precautions in order to prevent, hinder and counteract the operation bringing negative effects to human health or the environment. In 6 c. 11§ of the Environmental Code, it is stated that the EIA should describe what measures that are taken in order to prevent, hinder, counteract, or remedy the negative effects. As an interpretation of this, the Swedish Environmental Protection Agency have defined the concept of the mitigation hierarchy (Länsstyrelserna 2021).

There are measures that can be implemented to try to mitigate the negative effects on biodiversity that arise, in different ways. To prioritize the order of action, the mitigation hierarchy, which can be seen in figure 2.2, can be used as a tool. The first step is to classify the negative effect on biodiversity. When it is known, the next step is to avoid the negative effect as much as possible, by choosing the right location. Then, the next step is to minimize the negative effect. Further, the next step is to restore the natural environment. If these steps are not possible, ecological compensation can be done, either at the same place and same way as the original value or in another place and in another way compared to the original value. This can be done to reach no negative effect on biodiversity. It can also be done in order to gain net positive effect on biodiversity, either by the same natural value (net gain) or another natural value (net positive impact) (Nordström et al. 2021).

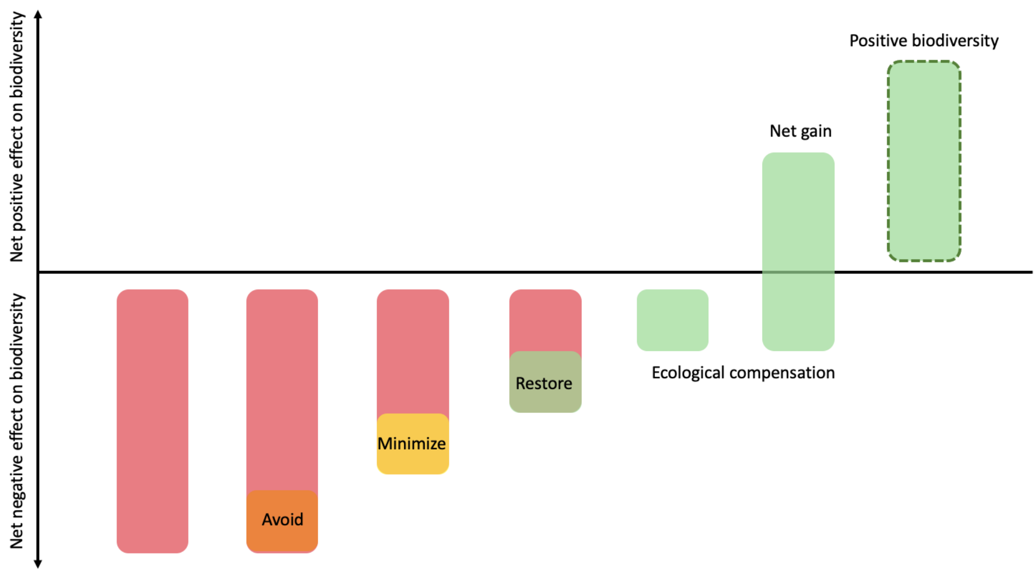

Figure 2.2: The mitigation hierarchy, adapted from Nordström et al. (2021).

Ecological compensation can come into question to make up for common interests that have been damaged by human activity. To restore or protect the same type of values that were lost is preferable, but values of another kind can also be sufficient in some cases. In the mitigation hierarchy as described above, ecological compensation is the last step that should be avoided as far as possible according to the Swedish Environmental Protection Agency. An operation must be admissible without compensation according to the Environmental Code. If the operation is admissible but there are unavoidable negative effects, ecological compensation can be discussed (Länsstyrelserna 2021).

A wind farm is classified both as an environmentally hazardous operation, covered in chapter 9 of the Environmental Code, and as a water operation, covered in chapter 11 of the Environmental Code. Although it cannot make the wind farm admissible, ecological compensation can come into question in some cases. In regards to water operations, ecological compensation can be done when the activity affects common interests, according to 16 c. 9 § in the Environmental Code, or fishing. For environmentally hazardous operations, ecological compensation can be done if the activity affects common interests or if it affects an environment quality standard (Länsstyrelserna 2021).

2.2.1 Positive biodiversity

There could be a case where only a positive effect is created, separately from the mitigation hierarchy. This is not classified as ecological compensation since it is not correlated to a negative effect, only enhancement of natural values on biodiversity or a specific species. This can be relevant with offshore wind power, since compensation is less supported in the Environmental Code at sea than on land. In that case, there would only be a green bar on the net positive side of the line called positive biodiversity, see figure 2.2. This is our chosen definition on enhancement of biodiversity and how to relate the definition to actual measures. This terminology is used throughout this master thesis.

Nature Positive is a similar concept established by Locke et al. (2021). The need to have a *Global Goal for Nature* similarly to the Paris agreement was identified. The goal "Net Positive by 2030" is to achieve a zero net loss of nature compared to a baseline of 2020. Thereafter, the aim is to achieve net positive biodiversity by 2030, changing the direction of the current trajectory of biodiversity loss and finally achieving full recovery by 2050. *Nature positive* can be achieved by for example focusing on species distribution, genetic diversity and the integrity of ecosystems. The need to put nature first is highlighted, pressing that the Sustainable Development Goals are dependent on that the goals related to the biosphere are met. A need is expressed for countries to protect and conserve areas and species. Companies should do their part by working towards a nature positive world.

Another concept called *nature-based solutions* touch on a similar matter, presented by Barber et al. (2020). It was developed during the UNFCCC in 2009 and was later described as actions that would protect, manage and restore natural or modified ecosystems. Some of the main criteria for choosing nature-based solutions is to prioritize halting the loss of natural ecosystems and combining biodiversity and climate mitigation. Synergies between action on climate change and biodiversity conservation is highlighted, and can create positive consequences when promoted together (Barber et al. 2020). This amplifies the need for measures directed towards enhancing biodiversity in offshore wind power plants.

3. Method

The methodology to reach the objectives with the master thesis is presented below. A literature review was performed to gather information to establish the current state of knowledge of how offshore wind power plants affect biodiversity. To investigate the effects, the meaning of the term biodiversity needed to be determined. To do so a general definition was sought and then narrowed down as to better represent the context of the thesis. This was done based on what is usually included in EIAs of wind power plants as well as inputs from interviewees.

The studied effects originating from the wind power foundations were chosen by first examining EIAs to get a perception of what is usually included. After that the effects were prioritized in consultation with Eolus Vind AB (in this report referred to as Eolus) as well as based on interview responses. The effects finally chosen were underwater noise, seabed habitat loss, resuspension and settling of sediment, reef effect, indirect effects, and cumulative effects. Information regarding the chosen effects was then compiled.

As a continuation of the literature review, information about measures to reduce the negative effects or increase the positive effects was collected. The measures for reducing negative impact were selected based on their relevance to the studied effects. An initial overview was formed by reviewing what measures are included in EIAs and then additional measures were sought. This was done primarily through citation chaining[1]. For the measures to enhance positive effects, the reef effect served as the starting point and measures aimed at its enhancement were sought. Most Nature Inclusive Design (NID) measures included were listed in a report by Hermans, Bos, and Prusina (2020), in which measures available on the market with enough available information were gathered.

The type of literature used were scientific articles and reports, reports from government agencies such as from the Environmental Protection Agency (*Naturvårdsverket*) and information from Eolus. Interviews were conducted with different agencies and scientists in order to gather knowledge and opinions. See table 3.1 for a full list of interviewees and experts. To gain a better understanding of the permitting process for offshore wind power, Malin Hemmingsson was chosen as she is listed as contact person for this topic at Swedish Agency for Marine and Water Management (SwAM)'s website[2]. To get input on species related to offshore wind power plants, the effect of larger wind turbines as well as measures to enhance biodiversity, people active within the field marine ecosystems were determined to be of interest. Birgit Koehler, Mattias Sköld and Linus Hammar Perry were chosen for their role as authors of publications of interest for the thesis or based on recommendations from other interviewees.

For an increased understanding of how large planned offshore wind power plants are assessed, different County Administrative Boards (CAB) were contacted. The County Administrative Board *Västra Götaland* were of great interest since they are preparing the application for the project West Wind which is subject for the case study. In order to increase the nuance of the interview results, the County Administrative Boards of *Halland*, *Skåne* and *Blekinge* were contacted, out of which *Skåne* was not able to participate. They were all chosen based on having a coast and having been asked to prepare an application for an offshore wind power plant according to the Government Offices of Sweden (Regeringskansliet 2023). The questions asked were kept the

[1] Utilizing the references from an article/report
[2] (Havs- och Vattenmyndigheten 2022b)

same for all CABs while they were adjusted to the respective expertise for the other interviewees.

The results from the literature review were applied to a case study of an offshore wind power project on the Swedish west coast. The project examined in the case study is owned by Eolus and is called West Wind. It was one of two possible project options provided by Eolus and was chosen due to the public availability of all information needed for this master thesis. The project was used to apply theoretical knowledge in a practical context, where potential design aspects to benefit biodiversity at a specific location was proposed.

For the analysis, certain topics were selected due to the fact they were highlighted as important by several of the interviewees. These topics were: role of NID in the permitting process, coexistence with fishery and future prospects. To analyse how NID could affect the permitting process the interview responses from the CABs and SwAM were used. For the other topics, contributions from all interview responses were used.

Table 3.1: Experts in marine ecosystems and County Administrative Board representatives that were interviewed.

Interviewee	**Organisation**
Malin Hemmingsson	Swedish Agency for Marine and Water Management (SwAM)
Birgit Koehler	SLU Aqua
Anna-Lena Olsson	County Administrative Board *Halland* (CAB H)
Linus Hammar Perry	University of Gothenburg (GU)
Mattias Sköld	SLU Aqua
Elin Smith	County Administrative Board *Blekinge* (CAB B)
Marcus Stenegren	County Administrative Board *Västra Götaland* (CAB VG)
Sandra Toivio	County Administrative Board *Västra Götaland* (CAB VG)

3.1 Delimitations

An initial limitation to the thesis was when deciding the effect on biodiversity from offshore wind power plants was restricted to subsurface marine biodiversity. Based on that, the focus was limited to the subsurface parts of an offshore wind power plant, and then further limited to foundations, thus excluding the cable network. The next limitation made was to focus on fixed foundations. It appeared difficult to compare fixed and floating foundations and out of the two categories there was a greater extent of material for fixed foundations. Within the fixed foundations category, a further limitation was made when choosing to focus on three types of fixed foundations. These three foundations are monopile, gravity and jacket which were chosen due to being the most common.

The design aspects and technological decisions were limited to subsurface adaptations with focus on foundations and scour protections. Measures aimed at enhancing the reef effect, but made for cable protection, were excluded due to cables not being in the scope of the thesis.

The life cycle of the wind power plant is limited to the phases of installation, operation and decommissioning. This means the manufacturing of the various parts of the wind power plant as well as their end-of-life treatment was excluded.

4. Theoretical background

In this chapter follows information regarding the characteristics of a wind power plant and legislation surrounding the permitting process. It contains a technical overview of a wind power plant, information about three different types of fixed foundations and a description of the life cycle of a wind power plant. Thereafter, there is a section regarding marine spatial planning and a section about the permitting process and how the impact assessment is carried out.

4.1 Wind power plant

The main elements of a wind power plant include the wind turbines, the foundations and the transmission system. Below follows an overview of the wind power plant with primary focus on the wind turbines and their components. The most prevailing wind turbine design is the three-bladed horizontal-axis upwind turbine (Bergström et al. 2022) and this design will serve as the reference for the description. An example of this turbine design can be seen in figure 4.1.

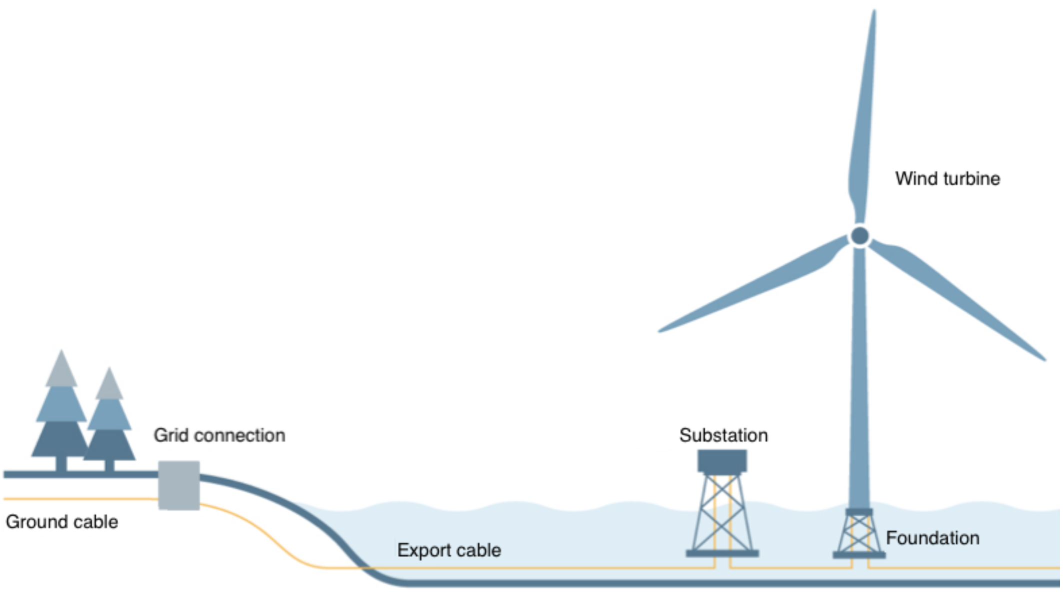

Figure 4.1: An overview of the system of an offshore wind power plant (Eolus 2024).

The rotor of the wind turbine includes the hub and the blades, where the hub serves as connection point between the blades and the main shaft and thereby the rest of the drivetrain (Manwell, McGowan, and Rogers 2009). Kinetic energy in the wind is harnessed by the blades and converted into rotational energy when the blades transfer torque to the drivetrain (BVG Associates 2019). For a wind turbine with a gearbox the drivetrain usually includes a low-speed shaft which is often called the main shaft, bearings, couplings, a gearbox, a high-speed shaft, and a mechanical brake and finally the generator (Manwell, McGowan, and Rogers 2009). The gearbox connects the low-speed shaft and the high-speed shaft with the purpose of speeding up the rotation. For a direct drive wind turbine, without a gearbox, the main shaft is connected directly to the generator instead of the gearbox. The function of the generator is to convert the mechanical energy to electrical energy (BVG Associates 2019). All of these major components, apart from the rotor, are housed in the nacelle to ensure they are protected from the weather (Manwell, McGowan, and Rogers 2009). In order to align the nacelle so that the rotor is oriented into the wind there is also a yaw system (BVG Associates 2019).

The nacelle itself is supported by the tower which comes in varying designs such as steel tubes, lattice structures, or concrete (Manwell, McGowan, and Rogers 2009). For offshore wind turbines the dominating design is the cylindrical steel tower. During maintenance the tower also provides access to the nacelle. Additionally, it also houses the electrical equipment, control equipment, and safety equipment (BVG Associates 2019). The tower is attached to a foundation, and this is often done with a transition piece. The whole wind turbine is supported by the foundation which anchors the wind turbine to the bottom. For foundations that are fixed to the bottom the structure reaches from the seabed to a couple of meters above the surface (Bergström et al. 2022). There are a number of foundation designs, some of which are described in detail in section 4.2, but in general they also provide a pathway for electrical cables as well as means of access to the wind turbine from the water (BVG Associates 2019). In the wind power plant, there is always an internal cable grid connecting the wind turbines to a transformer station, most often within the plant. From the transformer station there is one or more larger external cables that connect the plant to the grid (Bergström et al. 2022).

4.2 Types of foundations

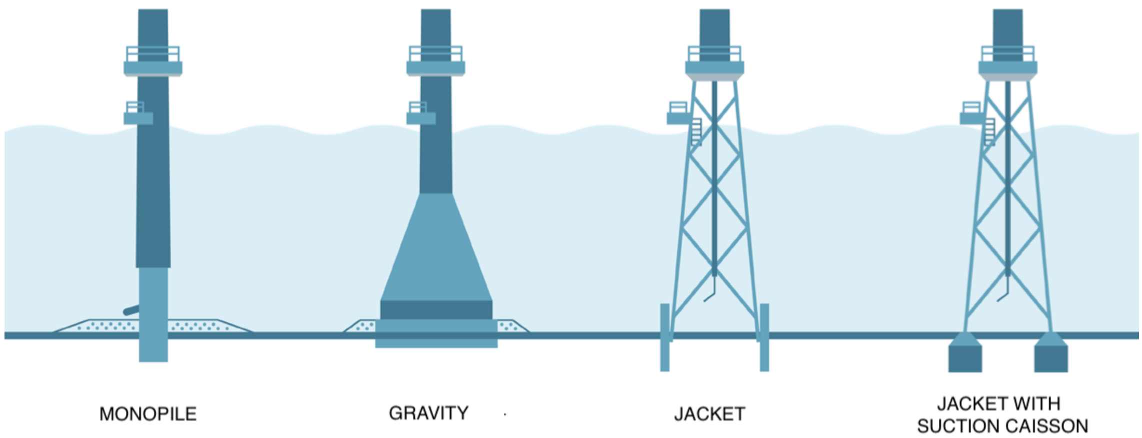

Figure 4.2: Types of foundations (Eolus 2024).

The most common types of bottom-fixed foundations are the ones in figure 4.2. Below is a summary of the most important characteristics of the respective foundations, presented in table 4.1. It can be concluded that the foundations have different applications as well as construction methods, causing them to affect the marine environment differently. Some aspects are decisive and are determined by the local conditions such as depth and suitable seabed conditions, making the choice of foundation clear. However, sometimes more than one option of foundation is applicable. In that case cost becomes a large factor and the least expensive option is typically chosen. There can also be a need to use different foundation types in one area, causing cost to be an important factor in how the project is realised.

Table 4.1: Comparison between characteristics of bottom-fixed foundations.

Characteristics	Monopile	Gravity	Jacket
Material	Steel	Concrete/steel container with ballast	Steel
Depth	<50 m	<30-40 m	>40 m
Suitable seabed conditions	Sand and clay	Rocky/hard/stable	From soft to hard
Structure	Cylinder	Conical/hourglass shape	Quadratic formation
Anchoring	Pile/suction bucket	Weight	Pile/suction caisson
Construction method	Piling/drilling	Dredging, paving, placement on seabed	Piling/drilling
Scour protection	Sometimes	Standard	Not often

4.2.1 Monopile

The monopile is the most common foundation in use worldwide (Horwath et al. 2020). It consists of a large steel cylinder, called a pile, that is driven deep into the seabed (Hammar, S. Andersson, and Rosenberg 2008; Horwath et al. 2020; Bergström et al. 2022). When driving the pile into the seabed the upper end can be deformed and so a similar steel cylinder is slipped over the embedded pile (Horwath et al. 2020). In order to protect the foundation from drift ice it can be equipped with an ice collar which is mounted at the water line (Hammar, S. Andersson, and Rosenberg 2008). Some monopiles are also equipped with scour protection (Horwath et al. 2020). However, this type of foundation is not dependent on scour protection since the erosion can be addressed by driving the pile further into the seabed during construction (Hammar, S. Andersson, and Rosenberg 2008).

The diameter of the foundation, the thickness of the steel as well as the depth of anchoring depends on factors such as water depth, weight and size of the wind turbine, characteristics of the bottom substrate along with the expected loads from wind, waves, currents and ice (Hammar, S. Andersson, and Rosenberg 2008; Horwath et al. 2020). To provide a sense of scale, Horwath et al. (2020) write that current designs are about 10 meters in diameter whereas Bergström et al. (2022) mention that it can vary between 10 and 18 meters. Driving the pile into the seabed provides support for both vertical and horizontal loads. The vertical loads from the turbine are supported by the bottom substrate under and along the sides of the pile. The horizontal loads are counteracted by the pile's bending resistance and the resistance of the bottom substrate surrounding the embedded section (Horwath et al. 2020).

Area of use for monopile foundation

The monopile foundations are best suited for sediments mostly consisting of sand and clay (Bergström et al. 2022; Horwath et al. 2020), preferably with a solid underlying bed (Hammar, S. Andersson, and Rosenberg 2008). It is also suitable for bottom substrates such as stone-mixed bottoms (Hammar, S. Andersson, and Rosenberg 2008). In areas prone to sediment movements, the monopile is suitable since it is driven deep into the seabed (SGS 2005 see Hammar, Andersson and Rosenberg 2008). Less suitable conditions for the monopile foundations are bottom substrates with a high density of boulders or coarse gravel, or where shallow bedrock is present (Horwath et al. 2020). This can prevent or make it more difficult for the pile to be driven to the desired depth. In difficult conditions such as stony bottoms, harder bottoms or occasional boulders, the pile can be drilled instead of driven (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022; Horwath et al. 2020).

When considering the depth at which the foundations are used, there has been a notable progress. Hammar, S. Andersson, and Rosenberg (2008) stated that, at the time, it was economically feasible up to a depth of 20–25 meters, depending on area and seabed conditions. More recently, Horwath et al. (2020) stated that the maximum depth for the monopile foundation is 50 meters.

This maximum depth will most likely increase with technical advancements and lower material costs.

Installation

The installation of monopile foundations normally does not require any preprocessing of the seabed (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022; Horwath et al. 2020). On the other hand, there is a substantial need for vessels with great lifting powers (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022) as well as strong tools for the pile driving (Hammar, S. Andersson, and Rosenberg 2008). The structure is usually prefabricated and transported to the installation site in one piece (Horwath et al. 2020). Once at the site, an installation vessel equipped with a crane positions the pile at the predetermined location, transitions the pile from a horizontal to a vertical position and then lowers it to the seabed (Horwath et al. 2020). It is of great importance that the vessels are kept in place during the installation and this is done using modern dynamic positioning systems (Horwath et al. 2020).

At first no driving is necessary due to the pile sinking into the seabed under its own weight (Horwath et al. 2020). In order to drive the pile deeper into the seabed it is then hammered or vibrated using a hydraulic pile-driver (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022). During this process the pile is subjected to heavy beats from the hydraulic pile-driver until the desired depth is reached (Hammar, S. Andersson, and Rosenberg 2008). The number of beats, the strength of the beats and the potential need for drilling are determined by factors such as the diameter of the foundation, the prevailing bottom conditions and the anchoring depth (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022). However, an average of 30 beats per minute at full energy is common (Bergström et al. 2022).

In case boulders or impermeable substrates are encountered, there might be a need for drilling (Bergström et al. 2022). To penetrate the material, the piling is haltered and a drill head is lowered into the pile (Hammar, S. Andersson, and Rosenberg 2008). If monopiles are installed primarily through drilling, the process involves a lining pipe – sometimes the pile itself – guiding the drill bit (Bergström et al. 2022). The lining pipe also prevents material from infiltrating and helps manage the spreading of the material within the pipe to the surroundings. During the drilling process, drill cuttings are transported up through the lining pipe and released at the seabed or at the surface (Bergström et al. 2022). When the pile is in place the next step is to connect the transition piece and it is then fixed into place with a concrete mixture (Hammar, S. Andersson, and Rosenberg 2008).

Suction bucket

An alternative technique for anchoring the monopile foundation is called a suction bucket. In its most basic design the construction consists of a cylinder with a closed top and an open bottom (Horwath et al. 2020). The structure, which resembles a large suction cup, is driven into the seabed and then fixed into place using vacuum (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022). This procedure is described by Horwath et al. (2020) and involves pumping out water from inside of the suction bucket in order to reduce the pressure and then letting the hydrostatic pressure of the water force the bucket into the seabed. The diameter of the bucket is determined by the horizontal forces it will be subjected to and so it needs to be large enough to resist the overturning moments. The vertical loads are mainly counteracted by the frictional resistance between the soil and the walls of the bucket (Horwath et al. 2020).

This technique for anchoring is commonly used for oil platforms and is ideal when there is no need for deep seabed penetration (Bergström et al. 2022). It is best used in areas with medium stiff clay or fine to medium sand, but less suitable for areas with rocky or hard bottom substrates (Bergström et al. 2022) as well as areas with very soft soils (Horwath et al. 2020). This type of anchoring is suitable up to depths of 30 meters (Horwath et al. 2020).

4.2.2 Gravity

The gravity foundation is a structure usually made of a concrete caisson or steel container filled with ballast (Bergström et al. 2022; Hammar, S. Andersson, and Rosenberg 2008; Horwath et al. 2020). The wide base rests on the seabed and the sheer size and weight of the foundation is what keeps the turbine tower upright (Bergström et al. 2022). The vertical loads from the wind turbine are transferred to the seabed and the horizontal forces, from wind, waves and currents, are counteracted by the weight of the foundation (Horwath et al. 2020).

The proportions of the foundation are dependent on the depth at the location, the size of the turbine tower, exposure to waves and streams as well as the ice conditions. To protect the foundations from the ice they can be shaped like an hourglass. This shape allows for the upper angle to break the ice (Hammar, S. Andersson, and Rosenberg 2008).

Horwath et al. (2020) compiled a couple of examples of wind power plants where gravity foundations have been used and the respective diameter for the base of the foundation. The projects Middelgrunden and Lillgrund are located in Öresund and both have base diameters varying between 16.5 and 19 meters for 2 and 2.3 MW wind turbines respectively. Additionally, the projects Nysted I (The Danish straits) with 2.3 MW wind turbines and Thornton Bank OWF I (North Sea) with 5 MW wind turbines are listed with the base diameters of 11 meters and 23.5 meters respectively.

A standard feature to incorporate for gravity foundations is a scour protection (Bergström et al. 2022; Horwath et al. 2020). The foundation can disrupt the current flows which in turn can lead to scouring of the seabed (Horwath et al. 2020). With the protection the risk of scouring is reduced, ensuring that the structure is not undermined (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022). The scour protection extends outward from the foundation to an arbitrary distance, usually 5-10 meters (Hammar, S. Andersson, and Rosenberg 2008). It is generally designed with a bottom layer of gravel covered by a layer of rock of varying sizes (Hammar, S. Andersson, and Rosenberg 2008).

Area of use for gravity foundations

Gravity foundations are best suited for shallow waters (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022; Horwath et al. 2020), limited by the cost, alongside size and weight. At great depths the foundation gets too large and too heavy (Bergström et al. 2022). For the concrete gravity foundations, the cost for construction and installation increases exponentially with depth (Hammar, S. Andersson, and Rosenberg 2008). In this aspect there is an advantage with steel gravity foundations, with their inexpensive production and installation, that does not increase exponentially (DWIA 2003 see Hammar, Andersson and Rosenberg 2008). For that reason they can be used in deeper waters compared to concrete gravity foundations (Hammar, S. Andersson, and Rosenberg 2008).

There has been an advancement during the last 15 years concerning depth. Hammar, S. Andersson, and Rosenberg (2008) stated that the gravity foundation was economically viable up to 10 meters in 2007. More recently Horwath et al. (2020) wrote that they are typically used for depths up to 20 meters but that they have been utilized in somewhat deeper waters. Today the gravity foundations are used at locations where the depth is 30 meters and the conditions for using gravity foundations in much deeper waters are good (Åkerström and Walfisz 2023).

Gravity foundations can be adapted to a variety of seabed conditions. It is advantageous because it can be used in areas where pile foundations are impractical or infeasible (Horwath et al. 2020). This foundation type can be adapted to different bottom substrates by adjusting the width of the base (Ståhle et al. 2017). Therefore, it is suitable for bedrock, terrain with boulders as well as stable compact sediment (Ståhle et al. 2017). The crucial aspect is an even bottom with good bearing capacity (Bergström et al. 2022). Consequently, it is not suitable for bottoms with loose sediments such as clay (Hammar, S. Andersson, and Rosenberg 2008).

Installation

Before the installation of gravity foundations, the seabed needs to be prepared in order to achieve a flat and level surface (Horwath et al. 2020; Bergström et al. 2022). The preparations involve dredging and then paving. Dredging is done in order to remove sediments and results in a hole in the seabed with specific measurements adjusted to the foundation (Hammar, S. Andersson, and Rosenberg 2008). In case large boulders are encountered they are fragmented through blasting (Hammar, S. Andersson, and Rosenberg 2008). After dredging the area is paved with a layer of crushed stones (Hammar, S. Andersson, and Rosenberg 2008). The area is then ready for the installation of the gravity foundation.

The foundations are built onshore and then transported to the site (Horwath et al. 2020). This can be done either on barges or by towing them (Bergström et al. 2022). It can be towed since the base is buoyant enough before it is filled with ballast (Horwath et al. 2020). Once the foundation has reached its location and the seabed is prepared it can be lowered into place by controlled flooding (Horwath et al. 2020). The next step is filling the base with ballast – high density materials such as stone or concrete (Hammar, S. Andersson, and Rosenberg 2008). When it is in place and has been ballasted, the hole surrounding the foundation is filled and finally the scour protection is added (Horwath et al. 2020). During the preparation and installation process, vessels are anchored either by using spud legs, computer-operated propellers or computer-controlled anchor ropes (Hammar, S. Andersson, and Rosenberg 2008). To ensure success, inspections are carried out by divers after completing each stage in the process (Hammar, S. Andersson, and Rosenberg 2008).

4.2.3 Jacket

A jacket foundation is made up of steel pipes (Bergström et al. 2022; Hammar, S. Andersson, and Rosenberg 2008) or steel beams in a network construction that is usually in a quadratic formation (Hammar, S. Andersson, and Rosenberg 2008). The pipes are either welded together or connected with the use of moulded sleeves (Bergström et al. 2022; Hammar, S. Andersson, and Rosenberg 2008). The foundation is anchored to the seabed by three or four connection points by piling (Bergström et al. 2022; Hammar, S. Andersson, and Rosenberg 2008) or by suction caissons (Bergström et al. 2022). The pile diameter used in planned wind power plants today is 2-4 meters (Andersson and Walfisz 2023). If it is a hard seabed, drilling can also be used in order to fix the foundation to the ground (Bergström et al. 2022). The tower of the wind turbine and the foundation is connected by a transition piece, in order to distribute the load evenly (Bergström et al. 2022; Hammar, S. Andersson, and Rosenberg 2008). It is possible to have a scour protection around the connection points of a jacket foundation, if the seabed conditions require so (Horwath et al. 2020).

Area of use for jacket foundation

For depths over 40 meters, the jacket foundation works well (Bergström et al. 2022). The technology is well tested since it is common in the oil industry (Bergström et al. 2022; Hammar, S. Andersson, and Rosenberg 2008). It can be used in shallow waters as well (Hammar, S. Andersson, and Rosenberg 2008), but is not cost efficient at around 20 meters and less, compared to other foundations. It is the least expensive foundation at large depths because less materials are needed (WPD 2005 see Hammar, Andersson, and Rosenberg 2008). It is expected that more projects in the future will use jacket foundations when establishing projects in deeper waters (Bergström et al. 2022; Hammar, S. Andersson, and Rosenberg 2008).

An example of an existing demonstration offshore wind power project that has used jacket foundations is Beatrice in the North Sea, described by Hammar, S. Andersson, and Rosenberg (2008). The foundations were installed at 48 meters depth and the turbines had a capacity of 5 MW. The four connection points were piled 44 meters deep into the seabed and the piles had a diameter of 1,8 meters. The steel construction was 62 meters high with the dimensions 20 × 20 meters at the widest part, closes to the seabed. The main part of the occupation of the seabed surface is because of the connection points, which is relativity small compared with other foundations (Hammar, S. Andersson, and Rosenberg 2008).

Installation

The installation process starts with piling the three or four connection points into the seabed. The foundation structure, consisting of the steel pipes in a certain design is mounted on top. Then there is a transition piece mounted on top of the steel construction that will be connected directly to the tower (Hammar, S. Andersson, and Rosenberg 2008).

Suction caisson

An alternative method to piling when anchoring the jacket foundation is using suction caissons (Bergström et al. 2022; Horwath et al. 2020). They are similar to the large suction bucket used for monopiles but smaller in size. Further, one caisson replaces each of the three or four piles otherwise used for the jacket foundation (Horwath et al. 2020). More about the installation principle as well as the suitable seabed conditions can be found in section 4.2.1.

4.3 Life cycle of wind power plants

The time needed for the different phases of a wind power plant is presented in figure 4.3. Before the wind power plant is installed, around two years goes into the planning phase. In order to be able to plan, a seabed investigation might be necessary, such as a seismological investigation using sonar or echo sounder (Bergström et al. 2022). Before installation can begin, it is necessary to get an environmental permit. What type of permit that is needed depends on the location of the planned wind power plant, described further in section 4.4. More information about the permitting process is found in section 4.5. Getting a permit can take a few years. After the permit phase, there will be a detailed design planning phase, which takes approximately three years. Then the installation phase takes place, which usually is requires a few seasons with good weather. When installed, the wind power plant is operational for a long time, around 30-50 years for plants planned today, depending on the technical advancements. Finally, the farm will be decommissioned which approximately spans as long as the planning phase.

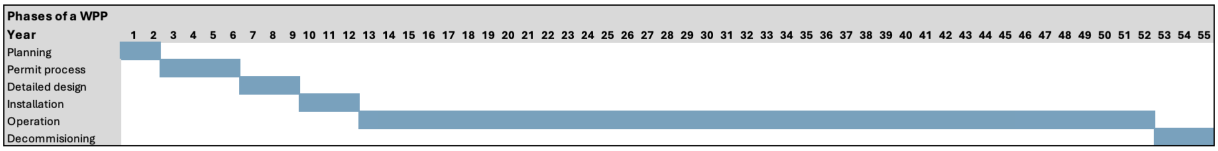

Figure 4.3: Estimation of phases in a life cycle of a wind power plant.

4.3.1 Installation phase

In the installation phase there are different steps which are described below according to Bergström et al. (2022). First the foundations are installed, and the approach depends on the type of foundation. More information about installation of foundations can be found in section 4.2. At the same stage that the foundations are installed, the transformation station and the connection cables are installed. The connection cables or the external cables are buried in the seabed and connected to the grid at a connection point. Then, the internal electrical grid is buried in the seabed. At last, the towers, the nacelle and the blades are mounted on the foundations. To ship all the parts out to the location, an increased amount of boat traffic can be expected, mostly in the form of prams and crane vessels. Since the construction work is difficult to carry out in the winter months, the whole installation phase usually takes one or two seasons. To install a single wind turbine when the conditions are right, the time needed is usually a couple of days.

4.3.2 Operational phase

In the operational phase, the wind power plant produces electricity to the grid. This phase is expected to last around 30 years, or longer. Depending on the conditions, there could be a need of replacing parts during the operational phase. Also there is a need for constant maintenance which means that there will be an increased amount of boat or helicopter traffic (Bergström et al. 2022).

4.3.3 Decommission phase

According to the international policy, the wind power plants should be dismantled when they are taken out of service (Bergström et al. 2022). The Swedish Environmental Code (SFS 1998:808) states that the operator is responsible to restore the area and dismantle the wind power plant after it is taken out of service. There are different ways to dismantle a wind power plant, and a variety of options on how much of the foundation that should be left in the sea. This depends on the local conditions and type of foundation (Bergström et al. 2022). A recommendation from Energimyndigheten (2016) is that the foundation is cut off at the seabed, and if there is a scour protection, it will stay. The connecting cables in the seabed should be removed. The different parts of the wind turbine, including blades, tower, nacelle and foundation are taken down and transported away for recycling or reuse (Energimyndigheten 2016). It can be expected that there are similarities between the construction phase and the decommissioning phase (Bergström et al. 2022).

The project owner must describe how the decommissioning affects the environment in the EIA. Normally it is not described in much detail but usually touches upon removal of cables and turbines and a discussion concerning removal of foundations. Removal of the foundation and scour protection could reverse the reef effect if it has been established (Hemmingsson 2024, SwAM). Decommissioning could also lead to environmental effects such as disturbance of the seabed, underwater noise and loss of protection from fishing (Fowler et al. 2018). This is usually handled by referring to a future investigation or a consultation with the CAB to determine how much is to be removed (Hemmingsson 2024, SwAM). SwAM accepts this type of description since they agree that after roughly a 30-year lifespan of the wind farm there may very well be a lot of new knowledge. For that reason, it may be beneficial to postpone the decision. Nevertheless, some kind of description has to be included and money has to be set aside for the decommissioning to ensure there are funds even if the owner of the wind farm goes bankrupt (Hemmingsson 2024, SwAM). Birgit Koehler (2024, SLU Aqua) describes that information from the control program, obtained during and towards the end of the operational phase is needed for a detailed EIA and planning of the decommissioning phase (Koehler 2024, SLU Aqua).

4.4 Maritime spatial planning

There are different maritime boundaries around Sweden which can be seen in figure 4.4. Closest to the coast is the inner zone and outside of this is the territorial zone, followed by the economic zone. Farther out is other countries' economic zones or international waters (Havs- och Vattenmyndigheten n.d). There are different actors that are responsible for planning depending on the maritime zone. In the inner zone as well as the territorial zone, the municipality is responsible for planning according to the Planning and Building Act (Boverket 2023). The Swedish Agency for Marine and Water Management are responsible for creating a proposal for the national maritime spatial plan, which the government will decide on. The plan is active for the economic zone as well as the territorial sea. An exception is one nautical mile outside of the inner zone boundary, where the maritime spatial plan is active if there are not any properties. The national maritime spatial plan and the municipality's planning have an overlap, where the national maritime spatial plan acts as a guidance to the municipality's planning (Boverket 2023).

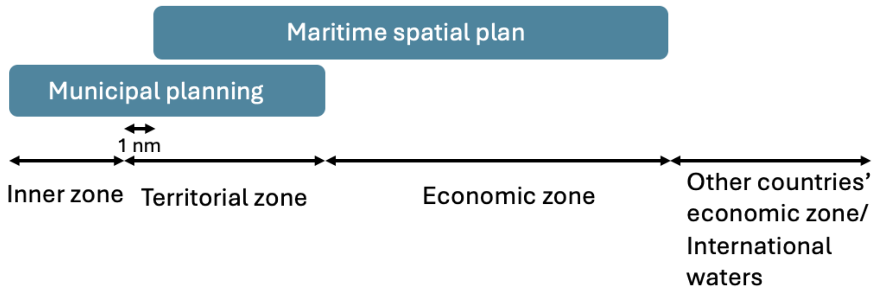

Figure 4.4: Maritime boundaries and planning responsibilities. Adapted from Havs- och Vattenmyndigheten (n.d).

If the wind power plant is planned inside the territorial zone, the Land and Environment Court (LEC) is responsible for the permission process and for the decision. The municipality also have to approve in order for the project to obtain the permit, also known as the "municipality veto" (Energimyndigheten 2024a). If the wind power plant is planned in the economic zone, the government is responsible for the permission process and decision (Regeringskansliet 2023). The EIA processes and laws differ across countries, and there are national marine spatial plans (Koehler 2024, SLU Aqua). There is also an environmental protection convention for Europe, Canada and the United States. It is called the Convention on Environmental Impact Assessment in a Transboundary Context (Esbo-convention) and has been ratified by Sweden. The Esbo-convention works with preventing environmental effects across countries' borders (Naturvårdsverket n.d).

There is currently an ongoing consultation with proposals for new maritime spatial plans which are to replace the existing ones. Hemmingsson (2024, SwAM) describes that in the new plans several areas suitable for energy production have been identified. In this process many trade-offs between different interests have been made. According to Hemmingsson, it is hard to find an area where there are no other conflicting interests, meaning some of the proposed energy areas are overlapping with such interests. Some of the areas for energy are overlapping with protected areas and several are overlapping with areas of national interest for commercial fishing. It is uncertain whether all proposed energy areas will be realized, the plans are more of an initial screening. In the end it will be the government's responsibility to evaluate what level of influence is manageable. In such cases it is important to monitor cumulative effects if multiple projects are granted permission in the same area (Hemmingsson 2024, SwAM).

4.5 Permitting process

Permission is needed to build offshore wind power. An EIA process according to the general rules in chapters 2, 3, 4, and 5 in the Swedish Environmental Code (SFS 1998:808) is necessary when applying for this permit (Havs- och Vattenmyndigheten 2022b). The process and permits necessary depends on the location of the offshore wind power plant, as mentioned in section 4.4. In the territorial sea, permission is needed in accordance with chapter 9, *Environmentally hazardous operation and health protection*, in the Environmental Code and in accordance with chapter 11, *Water operations*, in the Environmental Code. Endorsement from the municipalities where the wind farm is situated is also needed. The LEC is responsible for evaluating these permits (Havs- och Vattenmyndigheten 2022b). In a Natura 2000 area, a permit is needed according to chapter 7, *Protection of areas*, in the Environmental Code. The role of the CAB is as a referral authority and possibly as supervisory authority (Olsson 2024, CAB H).

In the economic zone, a permit from the government is needed according to the Act on Sweden's Exclusive Economic Zone (SFS 1992:1140) (Havs- och Vattenmyndigheten 2022b). If a Natura 2000 permit is needed in the economic zone, the CAB is responsible for evaluating and in order to get a permit for Natura 2000, you can not affect the species in the area in a considerable way. Otherwise, the role of the CAB in the economic zone is to prepare the applications when delegated to do so by the government, and then give a statement with their opinion back to the government (Olsson 2024, CAB H).

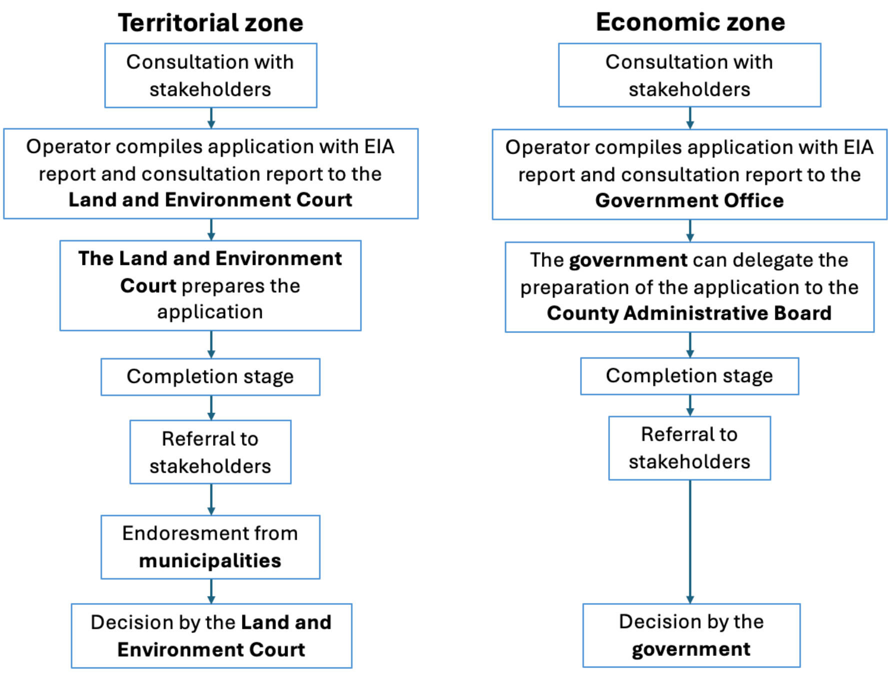

Figure 4.5: An overview of the permitting process for offshore wind power in the territorial zone and the economic zone.

The process in order to get a permit can be seen in figure 4.5 and differs between the territorial zone and the economic zone. The information about both the territorial permitting process (Energimyndigheten 2024a) and the permitting process for the economic zone (Energimyndigheten 2024b) is from the Swedish Energy Agency. The first step in both cases is to hold a consultation with stakeholders. Then, the next step for the operator is to compile an EIA report as well as a consultation report. If the wind power plant is in the territorial zone, the application is sent to the LEC who prepares the case. Simultaneously, other necessary permit processes take place. If the wind power plant is in the economic zone, the application is sent to the Government Office. Then the Government Office can prepare the application. The government can also delegate the preparation of the application to the CAB. After that there is a completion stage as well as referral to stakeholders. In the territorial zone, an endorsement from the affected municipalities is needed. Finally, a decision is made by either the LEC or the government.

4.5.1 Impact assessment

In the EIA application, the operator has the responsibility to present the environmental effects caused by the offshore wind power plant. To do this, the necessary basis must be provided, such as nature value inventory and a description of the surrounding environment. Further, these effects on the environment will lead to a consequence assessment on the impact categories. The impact categories are usually: *People and human health*, *animals or plants and biodiversity*, *land, earth, water climate, landscape and cultural environment, resource management of land, water and the physical environment, other resource management with materials and energy* as well as *other parts of the environment* (Andersson and Walfisz 2023). These environmental effects and the consequence assessment should be included in the EIA report.

To do the consequence assessment, there are different methods to use. In some environmental impact assessment reports for offshore wind power plants, the systematic approach presented in figure 4.6 is used and will lead to a specific result. The degree of impact is often graded on a scale including positive, insignificant, small, moderate and large. The degree of value and sensitivity is often graded on a scale including insignificant, small, moderate and large. This results in consequences that can be positive, insignificant, very small, small, moderate or large. These results are presented in the EIA report for the different impact categories that were described above.

Matrix for environmental impact asessment		Effects				
		Positive	Insignificant	Small	Moderate	Large
Values and sensitivity	Insignificant	Positive	Insignificant	Insignificant	Very small	Very small
	Small	Positive	Insignificant	Very small	Small	Moderate
	Moderate	Positive	Very small	Small	Moderate	Large
	Large	Positive	Very small	Moderate	Large	Large

Figure 4.6: Matrix for environmental impact assessment, adopted from Andersson and Walfisz (2023).

When the case is prepared by the CAB or the LEC, they review the application and assess whether they agree with the consequences on the impact categories or if they wish to see something else in the application.

4.5.2 Evaluation process of EIA report

There are set routines for how to work with biodiversity in the permitting process for the CABs, but it will vary depending on where the project is situated. The evaluation stage, where the application is prepared, is about reviewing the basis of the application. There are certain checklists that the CAB in *Halland* have developed (Smith 2024, CAB B), that some CABs use in order to perform the evaluation. There are many administrators in a matter, from different units in the CAB such as from the nature conservation unit (naturvårdsenheten), the preparedness unit (beredskapsenheten), the cultural environment unit (kulturmiljöenheten) and the fishing and environment conservation unit (fiske- och miljövårdsenheten). The company that applies produces the necessary basis such as bird inventory and fish inventory (Olsson 2024, CAB H). When compiling the EIA report, is important that all aspects are brought to light, all the problems and potentially the positive effects (Toivio and Stenegren 2024, CAB VG). The administrators read and uses the EIA report to perform the evaluation of whether the effects are admissible. The assessment is done based on experience from similar matters as well as from practice (case law) from the LEC (Olsson 2024, CAB H).

In the exclusive economic zone, there are no clear rules of who have precedence if two parties apply for permission in the same area. If there is competition, the government decides. For areas in the territorial zone where there is competition, chapter 16 in the Environmental Code applies, stating that you shall balance the interests and compromise. Then the LEC has the responsibility to determine in which way most benefit can be achieved (Olsson 2024, CAB H).

None of the environmental effects or impact categories are of higher importance or value than another (Toivio and Stenegren 2024, CAB VG: Olsson 2024, CAB H: Smith 2024, CAB B), all the aspects are considered before deciding (Toivio and Stenegren 2024, CAB VG). Which values that are the most important are unique to the different locations and sites (Toivio and Stenegren 2024, CAB VG: Smith 2024, CAB B), and a compromise is made to ensure what is best for that specific case (Toivio and Stenegren 2024, CAB VG). If there are important cultural environments, this may be taken into consideration. If offshore wind power is located far out at sea, biodiversity and species are considered very important (Smith 2024, CAB B). If a Natura 2000 area is located nearby, those species and habitats are highly valued (Smith 2024, CAB B; Olsson 2024, CAB H) and the consequences for these species are often focused on (Smith 2024, CAB B). The evaluation is very site specific and depends a lot on the seabed conditions (Olsson 2024, CAB H).

Since wind power contributes with renewable energy which is important for the climate, the impact category *climate* has a high importance. There will be a trade-off as to how much impact on the environment can be accepted (Olsson 2024, CAB H). The contribution to renewable energy is a positive environmental effect, but this is not weighed in as important when wind farms are compared to each other. All offshore wind farms produce renewable energy, which make them very similar in their positive contribution (Smith 2024, CAB B).

The SwAM acts as a referral authority in permitting process cases for offshore wind power. According to Hemmingsson (2024, SwAM) there is no overall ranking of the importance of the environmental effects in SwAM's assessment. However, underwater noise is important since it is one of the biggest effects. Hemmingsson suggests that this is because harbour porpoises are present in many areas in Sweden. They are very sensitive to underwater noise and have a high protection value since they are protected according to the species and habitat directive. Additionally, the porpoises in the Baltic Sea are acutely threatened. The porpoises are not as sensitive to, for example, resuspension and settling of sediment. The effect of resuspension and settling of sediment is quite temporary and often fairly local but can certainly have an impact.

5. Effects from wind power plants and measures for biodiversity

The following section compiles and presents information of how offshore wind power plants affect local marine subsurface biodiversity during the life cycle of a wind farm. This is done based on the knowledge that exists today and by an attempt to estimate the effects from future, larger wind power plants and cumulative effects based on the results from the interview study. What measures that can be taken to minimise the negative effects and enhance the positive effects are presented as well. The studied effects are noise, seabed habitat loss, resuspension and settling of sediment, reef effect, indirect effects, and cumulative effects.

Wind power affect the local biodiversity in the different phases of the life cycle. In the planning stage, investigations of the seabed are made which can cause noise. In the construction phase, there is noise from both construction and from boat traffic. The seabed will be occupied, and the local conditions changed. There is also resuspension and settling of sediments as an effect from the construction work. In the operational phase, there will be noise from vibrations created by the turbine. The tower, foundation and the potential scour protection will act as an artificial reef, which gives rise to what is called the "reef effect". In the decommissioning phase, depending on how much is removed, the reef effect could be lost. There can also be noise as well as resuspension and settling of sediments. The wind farm also gives rise to indirect effects such as constituting a protected area, providing a potential spillover effect as well as posing a risk for invasive species. Many wind farms in combination can contribute to cumulative effects.

5.1 Underwater noise

Sound waves are changes in pressure, caused by moving particles. Compared to sound in air, sound in water travels four times faster (Van der Meij et al. 2015). The sound distribution depends on the local conditions such as type of seabed. For example, a soft seabed absorbs more sound than a hard seabed and the sound waves decrease in intensity with further distance from the source. Additionally, thermoclines and haloclines can affect how the sound is distributed (Bergström et al. 2022).

Certain species use sound to communicate, navigate, catch prey or avoid predators, Thus, underwater noise can cause harm to marine species in different ways, described by Van der Meij et al. (2015). From the point of being audible, it can mask communication, cause them to avoid an area or damage hearing either temporarily or permanently depending on on the level and intensity of the noise. It can even cause injury or death to the marine fauna. There are threshold levels for noise, that are individual for specific species, called Temporal hearing Threshold Shift (TTS) and Permanent hearing Threshold Shift (PTS) (Van der Meij et al. 2015). This is measured in intensity, called Sound Pressure Level (SPL) and in exposure, called Sound Exposure Level (SEL). Additionally, there are different levels depending on if the sound is impulsive or non-impulsive. As an example, the PTS for porpoises for impulsive sound is SEL 155 dB re 1 μPa^2s (Bergström et al. 2022). The unit dB re 1 μPa^2s describes the accumulated sound energy over a period of time.

In investigations prior to the construction of a wind farm, in the planning stage, a lot of seismic investigations are performed, which can lead to high intensity sounds. If the wind turbines have monopile foundations, or jacket foundations attached with piles, there will be high intensity impulsive underwater noise when they are piled into the seabed (Bergström et al. 2022). Monopile will give rise to a higher sound level than jackets because of the larger pile diameter (Hammar, S. Andersson, and Rosenberg 2008). Piling takes between 4 and 6 hours and is most often done one foundation at the time (Bergström et al. 2022). There will also be an increased level of underwater noise because of increased boat traffic during the construction phase (Benhemma-Le Gall et al. 2021). If blasting is necessary for the construction, this will also generate high intensity underwater noise (Bergström et al. 2022). Activities like piling, dredging and seismic investigation also contribute to substrate vibrations (Hawkins et al. 2021).

During the operational phase, the gearbox and the generator produces mechanical vibrations that travel through the tower and propagate and generate underwater sound. The level of noise depends on the wind speed (Bergström et al. 2022). The frequency and intensity of the noise depends on the type of wind turbine, foundation and the attachment into the seabed (Hawkins et al. 2021). The operational phase causes mostly low frequency underwater noise (Tougaard, Hermannsen, and Madsen 2020). The highest level of operational underwater noise that has been measured according to Tougaard, Hermannsen, and Madsen (2020) is 137 dB re 1 μPa, for a turbine at a distance of 40 meters. Boat traffic can also be expected in the operational phase because of maintenance, causing noise (Bergström et al. 2022). When the wind farm is being decommissioned, high intensity underwater noise can be expected as well, from both boat traffic and construction depending on methods used (Bergström et al. 2022).

5.1.1 Affected species

Different species have varying sensitivity for high intensity underwater noise. The species most sensitive to high levels of sound is the harbour porpoise (*Phocoena phocoena*). There are threshold levels for when they usually are temporarily scared away, and higher threshold levels when permanent hearing damage can be caused (Bergström et al. 2022). Porpoises are the most common species out of porpoises, whales and dolphins in offshore wind power plants in the North Sea. They are also sensitive to starvation and require a lot of energy. Individuals have to trade-off between using energy to move from disturbance in a wind power plant, or tolerating it and staying (Benhemma-Le Gall et al. 2021). In a study, there was an observed 8–17 percent decline in porpoises when piling and construction were ongoing, showing that their behavior change during these activities (Benhemma-Le Gall et al. 2021). Other marine mammals such as seals are sensitive as well, but with a little higher threshold levels (Bergström et al. 2022).

One of the species groups where the sensitivity varies is fish. Sensitive species include herring as well as cod that have a swimming bladder while other fish such as mackerel is not as sensitive (Bergström et al. 2022). Vibrations in the seabed substrate cause particle motion, which fish and likely invertebrates can detect and be sensitive to (Hawkins et al. 2021). The effects on bottom living animals from high intensity sound vary a lot; some species are very sensitive while others are not. From the operational phase were low frequency noise occur, negative effects on benthic animals that are common on the Swedish west coast are not expected (Wikström and Granmo 2008).

5.1.2 Effects from larger wind power plants

In terms of noise there will be a difference when there are larger wind power plants, according to Hemmingsson (2024, SwAM). Piling a foundation with a larger diameter will give rise to louder underwater noises. The continuous noise during operation can also be a little louder for larger turbines (Hemmingsson 2024, SwAM). Linus Hammar Perry (2024, University of Gothenburg, GU) believes that the sound image during the operational phase will change when the wind turbines get larger. Partly because the turbine technique is made more efficient, which makes the sound less scratchy (Hammar Perry 2024, GU). When the wind turbines are much larger, there will be higher noise levels (Tougaard, Hermannsen, and Madsen 2020), and the higher noise will be spread to a larger area (Hammar Perry 2024, GU). Tougaard, Hermannsen and Madsen (2020) established that the size of the turbine is a significant factor for noise levels. In the study, a 13.6 dB increase was established for a tenfold increase in turbine power size. Although, the distance from the nacelle to the water will increase and the tower resonance will most likely change, making it hard to predict noise levels (Tougaard, Hermannsen, and Madsen 2020). There will probably be fewer wind turbines having a gearbox in the future, which could contribute to lower frequencies. Although at the same time the turbines are getting much bigger, making it a challenge to predict future sound levels (Bergström et al. 2022).

5.2 Seabed habitat loss

One of the main impacts on the seabed is the loss of original seabed habitat at the location where the turbines are placed (Enhus et al. 2017). The significance of this effect is partly determined by the size and the number of wind turbines (Bergström et al. 2022). It also depends on the foundation type since the area occupied differs, which has been described by Hammar, S. Andersson, and Rosenberg (2008). The foundation type that occupies the largest area is the gravity foundation. As mentioned in section 4.2.2, the gravity foundation is always paired with a scour protection which means that the area occupied extends beyond the size of the foundation. The scour protection usually extends 5-10 meters out from the foundation in all directions. The monopile foundation occupies a smaller area, especially without a scour protection. For monopiles with suction buckets the impact corresponds closest to that of the gravity foundation. Additionally, jackets also occupy a small area of the seabed, corresponding to the three or four anchoring points of the foundation (Hammar, S. Andersson, and Rosenberg 2008). Scour protections are common for monopiles and possible to use for jacket foundations. This would increase the occupied seabed area for the two foundation types.

In their study Wilson and Elliot (2009) exemplified with a monopile to calculate how large an area of the seabed that would be occupied. With a turbine tower diameter of 4 meters, giving an area of 12.5 m^2, and a scour protection extending 10 meters from the foundation, the total loss of area would be 452 m^2. The area occupied by scour protection in this case corresponds to 439,5 m^2. This information was then used in order to determine the net amount of habitat for different scour protections. The total habitat area created with a scour protection consisting of either gravel or boulders resulted in about 2.5 times the original habitat area, although of a different character for some locations (Wilson and Elliot 2009).

5.2.1 Affected species

The loss of the seabed can be seen as small in the context of the whole plant and the impact is local (Bergström et al. 2022). Yet, the organisms that lack mobility are at risk of being harmed or displaced (Bergström et al. 2022). Activities such as digging and drilling during the construction phase impact the benthic fauna and its environment (Enhus et al. 2017) and the recovery time of an area varies significantly (Bergström et al. 2022). The recolonization of areas that have been disturbed varies between locations as well as the type of disturbance. Bristle worms, roundworms, and crustaceans are quick to recolonize while mussels and other long-lived organisms take much longer (Bergström et al. 2022).

According to Bergström et al. (2022) there are no studies indicating that the establishment of wind power plants at depths of 30 meters or more, in areas predominantly characterized by soft seabeds, constitutes a threat to vegetation or bottom living organisms in the Swedish coastal areas. The same study also ascertained that, provided the fishing pressure does not increase within the wind power plant, the impact on benthic fauna such as the Norway lobster is more likely to be positive, rather than negative.

The establishment of a wind power plant could decrease the impact on the seabed if bottom trawling has been taking place in the area and this decreases or is no longer possible at all (Bergström et al. 2022; Enhus et al. 2017). Bottom trawling is closely connected to damaging the seabed and a decrease could then mean there would be an opportunity for the benthic community to recover (Bergström et al. 2022). The absence of trawling will have the most significant impact in *Västerhavet*, where most bottom trawling is done today (Hammar Perry 2024, GU).

5.2.2 Effects from larger wind power plants

Hemmingsson (2024, SwAM) suggests that it might be possible to look at the change in seabed impact mathematically. A larger turbine requires a larger foundation and a larger scour protection as well. On the other hand, the number of turbines might decrease. In the aspect of percentage of affected seabed, they might cancel each other out (Hemmingsson 2024, SwAM).

Hammar Perry (2024, GU) states that the wind power plants are getting larger, with longer distances of up to 1.5 km in between the turbines. In case trawling is restricted in these wind power plants, it results in larger areas where the soft bottom fauna can recover (Hammar Perry 2024, GU).

5.3 Resuspension and settling of sediment

There are two issues related to sediment. First the resuspension of sediments which increases the turbidity and later the deposition of the suspended sediment which results in a layer of sediment covering the seabed.

There is a risk for resuspension of sediment in connection to wind power plants, especially during the installation phase. There is often a need for preparations of the seabed before the installation of foundations and cables. Activities leading to resuspension of sediment particles include dredging, digging and drilling (Bergström et al. 2022). The largest impact is expected from either the installation of gravity foundations, due to the extensive need for seabed preparation, or installation of monopiles by drilling (Horwath et al. 2020). Both installations cause more extensive disturbance than installation of monopiles by pile driving. Additionally, installation of jacket foundations by piling causes less sediment disturbance than monopiles (Horwath et al. 2020). The installation of gravity foundations is the activity giving rise to the largest volume of sediment masses (Bergström et al. 2022). The difference between drilling and digging is that the sediment masses are more contained during digging which restricts the spreading (Bergström et al. 2022). Smallest amount of suspended sediment is expected when installing foundations with suction bucket since it involves little sediment disturbance (Horwath et al. 2020).

During the operational phase there are generally no activities causing resuspension of sediment (Bergström et al. 2022). On the contrary, if the wind power plant limits trawl fishing in the area, it could indirectly decrease the sediment disturbance (Enhus et al. 2017; Bergström et al. 2022). The presence of a wind power plant could lead to an increased deposition of particles close to the turbines (Bergström et al. 2022) which indirectly affects the turbidity. It could also lead to changes in the hydrodynamics which might affect how the suspended materials move and where they deposit (Bergström et al. 2022). Resuspension of sediments can also occur during the decommissioning phase. The extent is very dependent on the approach chosen for decommissioning but the effects are comparable to those during the construction phase (Bergström et al. 2022).

According to Bergström et al. (2022) the magnitude of the impact is closely connected to the local seabed conditions. A soft seabed consisting of materials with smaller grain size give rise to larger sediment resuspension compared to a seabed consisting of larger grain sizes such as coarse sand and gravel. Small and lightweight particles also spread further than large and heavy particles which means that the spreading can look different depending on what is studied. Elevated concentrations are generally limited to the proximity of the activity, referring to a few hundred metres up to a maximum of a kilometre away.

Two important aspects to consider when discussing impacts from resuspension of sediment are concentration of suspended materials and the duration of the exposure (Karlsson, Kraufvelin, and Östman 2020). In their study, Karlsson, Kraufvelin, and Östman (2020) looked at the effects on fish and crustaceans from dredging and dumping in aquatic environments based on the concentration of suspended materials in combination with the duration of exposure. They state that there are no clear limits for when increased turbidity has a negative impact on fish and crustaceans, instead it varies between different species, time of the year, the local environment, as well as the type of sediment. Nevertheless, what could be concluded was that few studies showed a direct negative impact on fish and crustaceans if the concentration of suspended materials was around 100 mg/l with an exposure time of 14 days for any water and sediment type.

5.3.1 Affected species

The species groups primarily affected are the fish and the benthic organisms (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022). As a result of construction activities a degradation of the benthic habitat in the nearby area occurs (Bennun et al. 2021). However, the benthic fauna is generally not affected negatively by a short-term increase of turbidity according to Bergström et al. (2022). They describe that natural resuspension of sediment is a part of habitats such as soft seabeds and many of the animals habitating these areas are consequently adapted to it. This means that environments where natural resuspension of sediment is rare are generally less resilient compared to environments with frequent natural mixing (Bergström et al. 2022). There is a risk that immobile benthic flora and fauna is covered, potentially leading to outcomes such as suffocation. These effects are considered relatively small and short-term (Enhus et al. 2017). The benthic vegetation is also affected by the increased turbidity due to less light penetrating which means the production and spread of bottom vegetation decreases (Hammar, S. Andersson, and Rosenberg 2008). Examples of sensitive plants are eelgrass (*Zostera marina*) and a group of green algae (*Charophyceae*) and the recovery time for this type of vegetation is long after a disturbance such as dredging (Bergström et al. 2022).

According to Bergström et al. (2022) the significance of the effect on fish is, among other factors, dependent on how much fish there is in the area as well as the species composition. If a population is concentrated in an area, such as during spawning, the risk of a larger impact increases (Bergström et al. 2022). Mobile species as well as those living in or near the sediment show higher resilience (Bergström et al. 2022). The different life stages of fish also exhibit varying levels of resilience (Karlsson, Kraufvelin, and Östman 2020). Adult fish are least sensitive due to the fact their gills are fully developed and they have the ability to move from the location (Kjelland et al. 2015). The increased turbidity can lead to avoidance, most likely due to sediment particles getting stuck in the gills making the uptake of oxygen more difficult (Hammar, S.

Andersson, and Rosenberg 2008). Additionally, a contributing factor is most likely also the reduced visibility. The most sensitive life stage is the larvae, when the fish is in between egg and fully developed individual (Moore 1977 see Bergström et al. 2022). The sediment particles can block the gills, making it more difficult to breathe for the larvae as well (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022). It also becomes more difficult to search for food and larvae can not go long without feeding (Bergström et al. 2022). Slightly less sensitive than the larvae are the eggs. Eggs are sensitive to a changed floating ability (Bergström et al. 2022). The sediment can stick to the eggs and weigh them down so that they sink to the bottom (Hammar, S. Andersson, and Rosenberg 2008). Cod (*Gadus morhua*) and European sprat (*Sprattus sprattus*) are examples of fish species with eggs floating in the water column (Bergström et al. 2022).

5.3.2 Effects from larger wind power plants

No information concerning how larger power plants will affect the spreading of sediment emerged during the interviews. A possible theory is that the spreading of sediment will be more extensive for larger wind power plants due to increased amounts of sediment removed when using larger foundations.

5.4 Reef effect

When introducing hard substrates in the form of foundations, there will be growth onto them from stationary plants and fauna. First, a biofilm of microorganisms will colonise the surface, making it easier for larger organisms to grow on it. After that, rapidly reproducing, opportunistic species will gather. Then the more competitive species will colonise the area as well. As a result of this, either because of aggregation or increased production, more mobile fauna will gather around the foundations, which is called the reef effect (Hammar, S. Andersson, and Rosenberg 2008).

When the report on environmental optimization of wind power foundations (Hammar, S. Andersson, and Rosenberg 2008) was published, the results had not been confirmed by many investigations. Since then, all new wind farms that have been built have become artificial reefs, with a high production of fish and growth, without any special design choices (Hammar Perry 2024, GU).

Langhamer (2012) states that there is an artificial reef effect caused by the introduced foundations and scour protection, which can have a positive effect on biodiversity, species richness and as a refuge from trawling activities. It can also have negative effects related to invasive species (Langhamer 2012). A Belgian study by Dagraer et al. (2020) also states that the underwater parts of the wind turbines act as artificial reefs and give rise to the artificial reef effect. This is described as changes in the ecosystem that lead to increased food production and refuge for both top predators and fish, which can be viewed as positive. Wind farms affect the marine ecosystem both structurally and functionally. The biodiversity increases as species establish on the structures. The hard substrate might introduce a new, more complex, habitat into the ecosystem. The first species group that colonise the structures are filtrators. They filter the water as well as provide food to the seabed communities which other species groups, in higher trophic levels, can benefit from (Degraer et al. 2020). It takes up to six years for the reef effect to reach its last succession stage (Bergström et al. 2022; Degraer et al. 2020), where a few competitive species grow on the foundation (Degraer et al. 2020).

There are different hypotheses on how fish benefit from offshore wind farms. It can either be that they are aggregated because of food availability, without increasing the population. Another theory is that the population is in fact increased because of the new structures that give them refuge and other benefits. Another point of view is that it can be non-beneficial because they are attracted to an area where they are more exposed to predators, a phenomenon called ecological trap (Degraer et al. 2020).

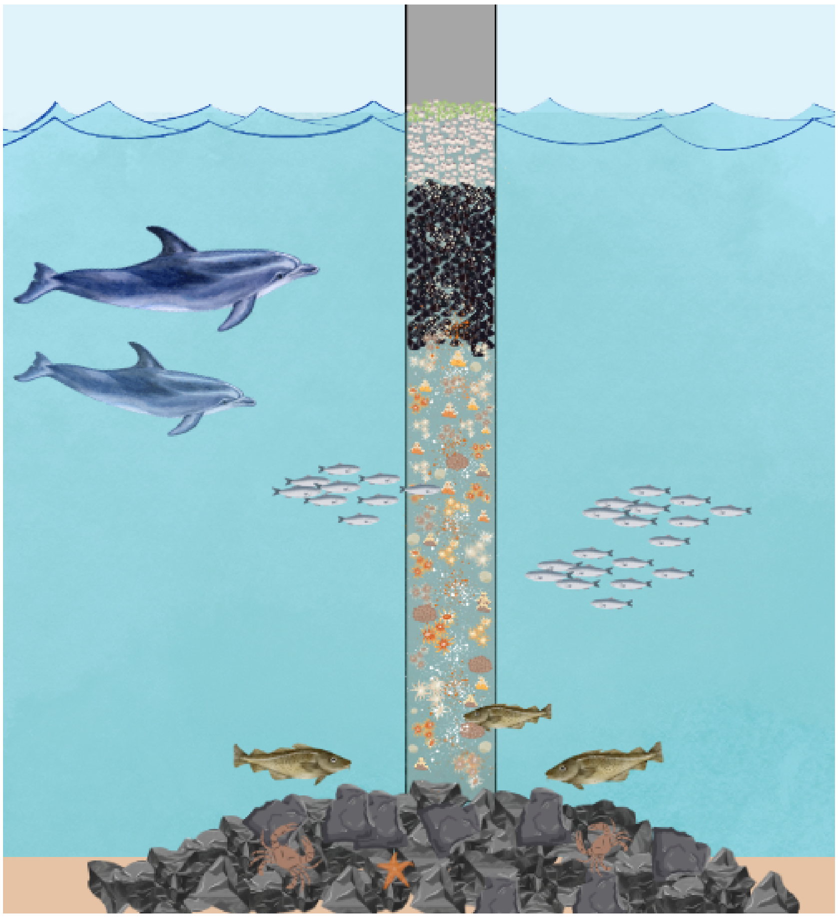

Figure 5.1: Illustration of zonation on a monopile foundation with scour protection. Made in Paint3D.

According to Sköld (2024, SLU Aqua) wind power plant will first and foremost benefit all organisms that grow on hard substrates. Since there are hard substrates in the entire water column, a zonation will take place (De Mesel et al. 2015), which can be seen in figure 5.1. At the areas of the foundation closer to the surface, called the splash zone, the species include barnacles (De Mesel et al. 2015), and mussels and algae (Sköld 2024, SLU Aqua; De Mesel et al. 2015). At the middle to deeper stage, there will be filter-feeding anthropods and anemones (De Mesel et al. 2015). At greater depths closer to the seabed there will be invertebrates sitting on rocks as well as fish that can find cavities to hide in (Sköld 2024, SLU Aqua). In the area surrounding the foundations, there will be crabs and lobsters (Krone et al. 2017).

The offshore wind farms can contribute to habitats for rare species in areas with soft seabed. The reef effect can help support local species as well as promote rare species and influence the geographical spreading of stationary species (Henry et al. 2018). These reefs can provide important ecosystem functions (Degraer et al. 2020).

How large the reef effect will be is dependent on several factors. Firstly, the location of the wind farm will dictate what kind of species that establish on the foundations. Factors that affect are salinity, currents, bottom substrate, and the distance to other hard bottoms

(Hammar, S. Andersson, and Rosenberg 2008). It can also be dependent on the distance to shore, depth, and light availability (Bergström et al. 2022). The introduced hard substrate will be of a larger area if there are more turbines in the wind farm and therefore more foundations. It is also dependent on the type of foundation and if there is a scour protection and how it is designed (Bergström et al. 2022). The foundations can contribute to two main types of hard habitats: Horizontal and vertical surfaces (Degraer et al. 2020). If there is a scour protection, there will be a new type of substrate in the form of rocks, and also a larger area in total which will enhance the reef effect (Bergström et al. 2022). A monopile foundation will be less colonised than a jacket foundation or a monopile with a scour protection (Hammar Perry 2024, GU). Hammar, S. Andersson, and Rosenberg (2008) concluded that for long term growth the type of surface material for foundations, for example concrete or steel, does not matter. Hammar Perry explains that scientists have placed wavepower foundations with drilled holes of different sizes in the ocean, to observe what kind of species that were attracted to them. The results showed that particularly crabs and lobster thrived, but also Norway lobster was observed around the foundation (Hammar Perry 2024, GU). As previously mentioned, depending on how the scour protection is designed, an increase of 2.5 times the lost surface area can be accomplished when introducing hard substrates (Wilson and Elliot 2009).

The reef effect will be centred around the foundations in the wind farm, but the created reefs also affect on a larger scale. It can affect commercial fish stocks (Wilding et al. 2017), increase connectivity[1] of benthic fauna, as well as increase connectivity for fish that benefit from hard substrates. Different species benefit from the wind farms in different ways depending on their feeding behaviour as well as their migratory behaviour (Degraer et al. 2020). When in the larval stage, organisms can travel up to tens of kilometres (Lacroix, Barbut, and Volckaert 2017) while fish can move hundreds of thousands of kilometres (Degraer et al. 2020).

The filtrating organisms that establish on the foundations take up plankton, and could contribute to better water quality if the wind farm is located where the water has high turbidity. Therefore it could lead to more light that reaches further down in the water column (Bergström et al. 2022; Degraer et al. 2020). The higher the salinity is in the water, the more marine conditions there will be and the reef effect will have a more positive effect. This is because species that are attracted to hard substrates usually thrive in marine environments (Bergström et al. 2022).

5.4.1 Affected species

According to Sköld (2024, SLU Aqua) it is difficult to say much about individual species. What can be said is that the foundations will offer an attractive habitat, like a wreck or a reef environment in an otherwise open seabed landscape. Particularly for species that like complex environments where they can hide or search for food. Overall, most fish, especially juvenile fish, will benefit from the installation since they like cavities where they can hide. Cod is a species that will benefit both from the fact that there are reef environments and the fact that it can hide (Sköld 2024, SLU Aqua). Cod thrives in wind farms, especially if the area is protected from fishing at the same time (Bergström et al. 2022). Dagreaer et al. (2020) states that finfish species, including Atlantic cod as well as pouting, black sea bass, and goldsinny occurs in offshore wind farms (Degraer et al. 2020). There is also an additional protection if the fishing in the area decreases because of closing the area to trawling (Sköld 2024, SLU Aqua). Close to the surface, an abundance of mussels and other filtering organisms will grow (Sköld 2024, SLU Aqua). The blue mussel is the most abundant species in offshore wind farms and have reef building qualities (Degraer et al. 2020). A bit deeper in the water column, the growth decreases but is still noticeable. Below a depth of about 20 to 25 meters there will be no growth

[1] Linkage of populations through spreading of reproductive elements

of algae (Sköld 2024, SLU Aqua). For species that move over large marine areas, like herring and mackerel, wind farms do not matter that much, unless several wind farms are located in a row and cover such a large area that it increases the survival of fish in a way that is shown at population level (Hammar Perry 2024, GU).

5.4.2 Effects from larger wind power plants

When larger wind power plants are established with larger distance between the turbines, up to 2–3 km, the effect on marine biodiversity is expected to be different compared to smaller plants. The reef effect is expected to be similar around the foundation, but with less connectivity compared to smaller plants. There is a need to do more research around this, because it is not possible to say directly that the effect will be the same (Koehler 2024, SLU Aqua).

Sköld (2024, SLU Aqua) believes that how the reef effect changes with larger wind power plants is possible to calculate mathematically. The reef effect will be larger the more hard surface area there is in a wind power plant (Sköld 2024, SLU Aqua). This can be done either by increased number of turbines, by larger foundations, or a combination. Hammar Perry (2024, GU) states that the reef effect will be concentrated around the foundations of the wind turbines. Although, the reefs are relatively small, especially in relation to the area of the entire farm (Sköld 2024, SLU Aqua). Because there are large distances between the turbines, there is an uncertainty if the reefs will benefit from each other. If higher connectivity is an objective, it could be a good idea to place artificial structures between the turbines (Hammar Perry 2024, GU).

In terms of the reef effect, Hemmingsson (2024, SwAM) speculates that if the foundations are small and close together, the effect might be more pronounced. Fish and small animals might perceive a bigger change in the environment when the foundations are closely spaced. Regardless, the reef effect will occur, as the settlement of algae and mussels will attract fish. However, it is very difficult to measure or estimate how much the effect means for this ecosystem in general (Hemmingsson 2024, SwAM).

5.5 Indirect effects

There are some effects not directly linked to one cause, but rather a consequence of many causes — both positive or negative for biodiversity. Indirect effects include that the wind farm area can become a protected area from fishing and a potential spillover effect caused by the reef effect and the protected area. Additionally, another indirect effect is the spreading of invasive species because of the introduction of hard surfaces and increased vessel traffic.

5.5.1 Protected area

Koehler and Bergström (2023) explain the prerequisites for coexistence of fishing and wind power. In Europe, boat traffic and certain types of fishing are usually not allowed in the wind farm area and an additional surrounding safety zone. Using moving fishing gear is usually not possible while use of stationary fishing gear can be possible. This is because of risks associated with activities inside the wind farm. There is a risk of collision with the wind turbines and that fishing gear gets stuck on the turbines or cables if they are not properly buried in the seabed. The insurance costs could be high for the fishermen if they would continue fishing in the area. In some countries, certain types of fishing can be possible, but fishermen tend to avoid the areas because of the previously mentioned risks. Bottom trawling is especially risky due to the trawl scraping the seabed, which leads to even higher risk of getting stuck or damaging the cables (Koehler and Bergström 2023). In Sweden, fishing can be combined with wind power depending on each specific case. For example, in the planned wind farm Galene, passive fishing is expected to be possible (Klimat- och näringslivsdepartementet 2023).

Larger distances between turbines in the future due to increased efficiency can make it easier to combine fishing with wind farms, perhaps making the protected area less effective (Koehler and Bergström 2023). If fishing and other human activities are avoided in the area, marine flora and fauna will have a safe zone to thrive since trawling contributes to a great impact on biodiversity and habitat loss. This will also enable both juvenile and older fish to survive for longer (Langhamer 2012).

5.5.2 Spillover effect

Langhamer (2012) explains that the spillover effect is when the wind farms support higher survival rates of fish which leads to higher catch rates outside of the wind farm. This occurs partly because of shelter from trawling as mentioned above, and partly by provision of food from the reef effect. The positive effects on fish catching rates are not confirmed and can differ between species, but generally, fish stocks are increased around artificial reefs. If an offshore wind farm would become a protected area, free from fishing, it will further contribute to the spillover effect. A risk associated with the spillover effect is a potential increase of fishing around the wind farm (Langhamer 2012).

5.5.3 Invasive species

The introduction of new species can cause large effects on the local ecosystem and even the global biodiversity (Langhamer 2012). Generally, most invasive species relevant in the case of offshore fixed foundations are the ones habitating hard substrates since they gain establishment routes (Sköld 2024, SLU Aqua). Yet, this is not always the case since there are differences in the habitats between artificial hard structures and natural hard substrates (Langhamer 2012). However, many of the species are already here and the presence of hard bottoms is not a limiting factor in their ability to spread along the coastal stretches. If anything, it could be an important factor to consider for their ability to spread between sea areas (Sköld 2024, SLU Aqua).

In the widespread oceans, where wind farms are being built, there are not a lot of hard substrates in the water column — especially not close to the surface, in the splash zone, which creates a free niche. In shallow waters, the highest amount of non-indigenous species are found in the splash zone (Degraer et al. 2020). There are fewer records of non-indigenous species found in wind farms in the subtidal zone, but there is still a concern. Although, there is no documentation that wind farms cause increased amount of non-indigenous species (Degraer et al. 2020).

An example of an invasive species present in waters on the Swedish west coast is the Pacific oyster (*Crassostrea gigas*). The oyster could settle on wind turbine foundations but they are already widespread and so it is uncertain whether additional settling spots provided by a wind power plant would amplify this issue. However, it might become of bigger concern if multiple wind power plants are placed in close proximity (Sköld 2024, SLU Aqua). Hammar Perry (2024, GU) believes that the Pacific oyster is already established at the Swedish west coast, and that we will never get rid of it. It would not spread long distances because of a wind farm, rather because of ships and climate change (Hammar Perry 2024, GU).

Wind power foundations allow species to establish, potentially causing a stepping-stone effect (Sköld 2024, SLU Aqua). If there is an area where there are no natural reefs at all and then a lot of wind turbines are built, new species might be able to establish in this new area (Hammar Perry 2024, GU). Hemmingsson (2024, SwAM) also believes that there is always a risk of invasive species when new elements enter the marine ecosystem. When these hard structures are introduced, they can attract new species that suddenly find an environment to grow on. It is a potential negative effect and if there are several farms established along the coast it can result in a stepping stone effect (Hemmingsson 2024, SwAM). Although, according to Hammar Perry (2024, GU) this is very theoretical. He believes the process will happen anyway, only perhaps a bit faster with the aid of wind power. Invasive species should be closely monitored, especially in soft bottom areas (Hemmingsson 2024, SwAM). Most species can manage to transport themselves over clay seabed, and these distances are not what prevents a species moving from one place to another (Hammar Perry 2024, GU). This issue with invasive species already exists due to ship traffic (Sköld 2024, SLU Aqua). There is ballast water that works as a vector between continents (Hammar Perry 2024, GU, Langhamer 2012) and buoys that are put out that organisms could grow on. In comparison with other processes, establishing a wind farm is not a large issue in the aspect of invasive species (Hammar Perry 2024, GU).

5.6 Cumulative effects

There are currently multiple wind farms being planned right next to each other along the Swedish west coast north of Gothenburg, see figure 5.2. If all these will be built, there is a risk for cumulative effects.

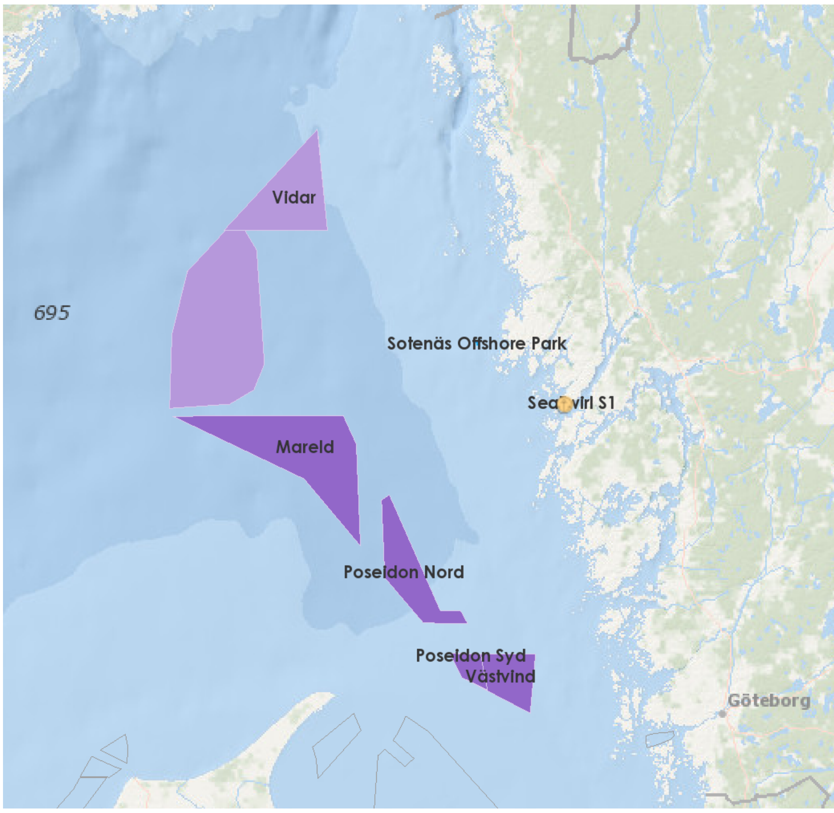

Figure 5.2: Planned offshore wind farms along the Swedish west coast north of Gothenburg (4C Offshore 2024).

According to Sköld (2024, SLU Aqua) the biggest challenge and uncertainty for coexistence of nature conservation and offshore wind power is the cumulative effects when multiple large farms are built. There is no knowledge about how it will affect large migration patterns for different species, such as fish which migrate to their spawning grounds. The effect from one farm is not of much significance, but if there are several ones all the way along Kattegat and

Skagerrak it is difficult to determine the impact (Sköld 2024, SLU Aqua).

Sköld (2024, SLU Aqua) believes the conclusions previously drawn, including that many of the effects are quite marginal, are valid also for larger wind power plants. He also points out that what is unknown, and difficult to predict, is what the effects would be if you place several wind power plants in a row throughout Skagerrak and Kattegat (Sköld 2024, SLU Aqua).

There is no standardized method that all companies use to account for their potential cumulative effects, but all companies shall describe it in their EIA report. Potential cumulative effects on different temporal and spatial scales, as well as their assessment, are currently also intensively scientifically studied and evaluated (Koehler 2024, SLU Aqua).

According to Hammar Perry (2024, GU) everything is a question about scale. The North Sea has changed for a long time because of bottom trawling. Now when a lot of wind power is planned in the area, the ecosystem will change a lot. There will be a lot more reef structures and hard bottom associated organisms. Filtrating organisms will purify the water from eutrophication. There will be an especially large difference in areas like the sandbank Dogger Bank in the North Sea, where the fishing has been hard on the natural reefs for a long time. These changes will cause a shift towards what the area looked like 200 years ago (Hammar Perry 2024, GU).

According to Hemmingsson (2024, SwAM) the cumulative effects vary depending on the aspect considered, but they certainly exist. A negative aspect, such as noise or non-indigenous species, becomes more prominent if there are more wind power plants in the same area. Some say wind farms could act as a refuge for fish and that in terms of this aspect it would be positive with several adjacent wind farms so that the effect could spread. Hemmingsson (2024, SwAM) states that there is not enough information about this effect and there is also a great difficulty in how to measure it. The cumulative effect for commercial fishing becomes clear when multiple wind farms are being built in fishing areas, assuming that fishing would be restricted. This means that there would be less areas for commercial fishing (Hemmingsson 2024, SwAM).

5.7 Measures to minimise negative effects

To mitigate the negative effects, it is important to consider the environmental impact early in the project process. This includes choosing an appropriate location, making conscious design choices as well as carefully planning the installation. The purpose of choosing a suitable location is to prevent degradation or loss of sensitive habitats, minimize barrier effects as well as lowering the risk of mortality for species associated with these habitats (Bennun et al. 2021). Examples of areas that should be avoided during the planning stage are marine protected areas, areas supporting threatened species or ecosystems such as breeding grounds as well as areas that concentrate species' movements such as sandbanks (Bennun et al. 2021). In accordance with this, Hemmingsson (2024, SwAM) acknowledges the importance of choosing the right location. SwAM believes that as a primary cause of action, Natura 2000 areas with highly sensitive environments should be avoided (Hemmingsson 2024, SwAM).

Design choices include choosing a foundation type and as can be read in section 4.2, the different foundation types have different properties. Depending on the area, the choice can be made based on the needs of lowering the construction noise or decreasing the need for seabed preparations (Bennun et al. 2021). The choice of foundation also determines the need for scour protection which in turn increases the availability of hard substrates (Bennun et al. 2021).

The negative impacts occurring during the installation can be avoided or minimized by scheduling specific activities to strategically chosen time frames (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022; Bennun et al. 2021). This includes avoiding disturbing species during sensitive periods such as marine mammal breeding and migration as well as fish migrations, and spawning. Ideally the installation should be put on hold during these periods. Avoiding sensitive time periods is one of the most effective ways of mitigating negative effects during the construction phase (Bennun et al. 2021).

To determine the optimal timing the local conditions and the species composition needs to be known (Karlsson, Kraufvelin, and Östman 2020). In Swedish waters, one tool that can be utilized is called *Lektidsportalen* which is a collaboration between SwAM and SLU Aqua (Havs- och Vattenmyndigheten 2022a). It was created with the aim to identify in which Swedish waters different fish and crustacean species are present and during what part of the year the different species are most susceptible to environmental impacts. The tool includes the sensitive periods; spawning, spawning migration, larval development, egg development, combined spawn/egg/larval stages, accumulation at birth and winter hibernation. Results are given by county and for four different water types. The most sensitive period for each species is presented and when combined they yield a sensitivity index for each month, giving an overview of the most critical months overall.

The installation of offshore wind power plants is dependent on weather and wave height which limits the construction period. This in turn limits the extent to which the installation period can be adjusted to mitigate biodiversity impact (Bennun et al. 2021). In a situation where it is difficult to find a suitable time period, additional protective measures can be implemented to minimize negative impacts. Some potential measures to minimize negative effects from underwater noise, seabed habitat loss and resuspension and settling of sediment are explained in more detail below. A summary of the measures that can be implemented to minimise negative effect are presented in table 5.1.

Table 5.1: Measures to minimise negative effects.

Effect category	**Measure**	**Outcome**
Underwater noise (installation phase)	Double Big Bubble Curtain	- 8-18 dB (SEL)
	Soft start	Deter fauna
	Ramp up	Deter fauna
	Hydrosound Damper	-10 dB (SEL)
	Blue piling	-20 dB (SEL)
	Passive Acoustic Monitoring	Monitor fauna
	FaunaGuard	Deter fauna out of PTS zone
Seabed habitat loss	Micrositing	Avoids sensitive habitats
	Placement in deep water	Avoids sensitive habitats
Resuspension and settling of sediment	Choice of dredging equipment	Minimises sediment resuspension
	Geotextile	Minimises spreading of sediment
	Bubble curtain	Encloses sensitive areas
	Sheet piles	Minimises spreading of sediment

5.7.1 Underwater noise

Many protective measures for underwater noise are standard today, such as using bubble curtains, soft start and ramp up (Koehler 2024, SLU Aqua). Bubble curtains are effective for reducing the noise (Bergström et al. 2022). They work by using compressed air through hoses laying on the seabed, creating air bubbles that rise in the water pillar due to pressure differences. If using a Double Big Bubble Curtain, around 8–18 dB (SEL) reduction while pile driving can be expected, but it depends on water depth and applied air volume (Bellmann et al. 2020). When piling, a soft start is first performed, with high frequency but lower intensity beats, which can be used to scare away fauna. A gradual ramp up of intensity is then performed which is necessary in order for the piling-machinery to work, but also deters animals (Bergström et al. 2022). Hydrosound Damper and blue piling are other measures that will decrease the creation of sound during the piling (Bergström et al. 2022). A Hydrosound Damper consists of a large net with foam elements mounted on it. With a Hydrosound Damper, noise reductions of 10 dB (SEL) can be obtained (Bellmann et al. 2020). The blue piling concept works by reducing the pile vibrations with the help of water mass as a pushing force and can reduce sound levels of up to 20 dB (SEL) (IQIP n.d).

There is another method called Passive Acoustic Monitoring, that can be used to discover mammals with the help of sound, but this systems is often not used in isolation (Van der Meij et al. 2015). Acoustic Harassment Devices are measures to scare away animals (Bergström et al. 2022). There is a measure that is called FaunaGuard which is used in the Netherlands and explained by Van der Meij et al. (2015). FaunaGuard uses sound to deter species that may be affected by underwater noise or physical disturbances from construction. By emitting sound that cause marine fauna to move from the area before construction activities, damage to marine fauna can be avoided. The FaunaGuard is tested and customized for specific species or species groups, by selecting for example the appropriate frequency and sound levels. The FaunaGuard has been used during construction for a wind farm in the Dutch North Sea, with the objective species being the harbour porpoises. They were deterred around 1 km away from the construction activity to avoid the risk of PTS on porpoises (Van der Meij et al. 2015). The scaring-devices should be used carefully since high intensity sound can be emitted (Bergström et al. 2022).

5.7.2 Seabed habitat loss

The most important part for mitigating negative effects on the seabed is to avoid placing the wind farm in a particularly sensitive environment (Bergström et al. 2022). Even if areas such as Natura 2000 are avoided there is no guarantee that the location does not hold valuable habitats (Hemmingsson 2024, SwAM). For that reason, protective measures such as micrositing can be used. It is used to avoid placing the foundations in sensitive areas within the project site of the wind power plant (Bennun et al. 2021). According to Hemmingsson (2024, SwAM) this can be done by carefully examining the seabed, for example by filming, to inspect each location where the foundations are to be installed. A discussion can then be held with, for example the CAB, regarding the placement of each individual foundation. By doing this, valuable habitats can be detected and a safe distance to these habitats maintained (Hemmingsson 2024, SwAM). The risk of disturbance could also be decreased if the turbines are placed in deep waters, at depths where the sunlight cannot reach the seabed. The occurrence of species that can be disadvantaged is less likely at that type of location (Bergström et al. 2022).

5.7.3 Resuspension and settling of sediment

As previously mentioned, the activities mainly giving rise to sediment resuspension are dredging, digging and drilling which occur during the installation phase (Bergström et al. 2022). For offshore wind power the extent of dredging and the resulting resuspension is small and brief in relation to other dredging projects (Hammar, S. Andersson, and Rosenberg 2008). With utilization of measures to reduce the resuspension of sediments, the effect on the benthic organisms is expected to be small and local (Bergström et al. 2022).

A guide has been developed by SwAM in order to assist with reviewing and supervising dredging and handling of dredged masses according to the Environmental Code (Havs- och vattenmyndigheten 2018). Among other things it includes descriptions of dredging techniques and measures to limit negative environmental effects. The importance of timing is highlighted, especially for resuspension of sediments. Generally, it is recommended to avoid the period March/April to September/October for performing dredging and other activities causing resuspension. As this might not be possible the protective measures can be considered, both for decreasing the resuspension and limiting the spreading of resuspended sediments (Havs- och vattenmyndigheten 2018).

SwAM describes that the magnitude of impact from dredging is largely dependent on the choice of technology and the logistics of its implementation. They point out that local conditions play a crucial role when determining the appropriate technology and the necessary requirements. When choosing dredging equipment, the main technologies are bucket dredging, also known as excavation dredging, along with suction dredging. They mention that suction dredging causes less sediment dispersion than bucket dredging and describe an option called environmental bucket dredging. It is constructed to enclose the sediment fully in order to decrease the spill and thereby the resuspension of sediment (Havs- och vattenmyndigheten 2018).

In the guide it is explained that to decrease the spreading of resuspended sediment the area of dredging can be enclosed. They describe three different types of protective screens called geotextile, bubble curtains, and sheet piles. The geotextile is a fabric which stretches from the surface down towards the bottom, preferably all the way. It can be placed around the dredging area or to shield sensitive areas nearby. It is kept vertical by weights at the bottom but is not the most suitable option in waters with a lot of movement. Bubble curtains have been mentioned for noise mitigation and the principle of bubbles creating a barrier is the same. However, for protection against resuspended sediments it is placed around the area which is to be protected. It works best for shorter stretches in waters with less movement. The sheet piles are made of wood, steel or plastic and extend throughout the water column. Installation of the sheet piles can be difficult in waters with more movement, but once in place they work well. On the downside, this method is expensive for shorter use and the installation and removal cause noise (Havs- och vattenmyndigheten 2018)

Disposal of the dredged masses is often referred to as dumping. SwAM express that choosing a suitable location and time period is very important for this activity as well. Again, Natura 2000 areas, nature reserves, and water protection areas are considered unsuitable locations. They explain that if dumping occurs in the water, the seabed at the dumping location should be of the same material as the dredged masses. The same type of measures used for dredging can also be used for dumping. Additionally, dewatering the dredged masses before dumping can limit the resuspension of sediments. Information regarding handling of polluted sediments is also available but this topic lies outside the scope of this study (Havs- och vattenmyndigheten 2018).

5.8 Measures to enhance positive effects

Offshore wind farms can contribute to unwanted effects but can also play a part in enhancing biodiversity. This makes it important to characterize and define the aim and the wanted effects to optimize the potential benefits. A broad understanding is also important in order to be able to design Nature Inclusive Design (NID) structures (Degraer et al. 2020). NID is a term for measures and solutions that are designed in order to enhance the habitats for species and ecosystems, both by adding structures and designing in a specific way. Positive biodiversity, mentioned in 2.2 can be achieved by using NID.

If structures are placed between wind turbines, in a wind farm with larger distances between turbines, this could increase connectivity for certain species, which could imply advantages or disadvantages depending on the specific situation (Koehler 2024, SLU Aqua). In some environments it could be valuable to build artificial reefs. For example, it could be beneficial to distribute fish hotels throughout the whole wind power plant area (Hammar Perry 2024, GU). How well the measures will work depends on, among other things, the depth of the location, size of the foundations, and where in the water column the structures are placed. In general, the more cavities generated, the greater the impact from a reef perspective (Sköld 2024, SLU Aqua).

Another type of measure is to restrict the wind power plant area from fishing and other activities, resulting in a protected area. This could be done on the whole wind power plant area or a smaller part of it. The benefits include a chance for benthic species to recover from negative effects caused by bottom trawling and higher survival of fish which could lead to population growth and spillover effects.

5.8.1 Design of foundations and scour protections

When designing the foundations and scour protections, it is important to be aware of what species that you want to benefit. Some aspects are very species specific and some are more general for all fauna. For the material of the foundation, most species tend to prefer concrete over steel (Bergström et al. 2022). The shape of the foundation also matter since macroalgae prefer horizontal surfaces while filtrators dominate on vertical surfaces (Hammar, S. Andersson, and Rosenberg 2008; Bergström et al. 2022). Mobile fauna such as fish and crabs enjoy cavities and when the foundation has an overhang (Bergström et al. 2022). Overhang on gravitation foundations also benefits filtrators but not algae, since it blocks light that the algae need (Hammar, S. Andersson, and Rosenberg 2008). When it comes to the larval stage, most species prefer a more rugged surface to be able to settle.

For the scour protection, a wide variety of shapes and materials will benefit fish and more layers of rocks and blocks will benefit mobile fauna (Bergström et al. 2022). Rock is the most common material for scour protections while aggregate for concrete such as gravel facilitates adjustment of the design. Furthermore, a mix of materials in the scour protection could be beneficial since it reflects the naturally occurring range of habitats (Glarou, Zrust, and Svendsen 2020). With varying cavities of different sizes, many different species can thrive. It can also benefit different stages of the same species. The more complex the structure, the larger the reef effect can become (Bergström et al. 2022). Boulders compared to gravel will contribute to larger ecological conservation benefits (Langhamer 2012). A complex structure is positively correlated with both fish abundance and diversity. Complexity can be achieved by providing a variety of crevice sizes, which in turn can be accomplished by using a mixture of different sized rocks. To adjust the complexity, it is also possible to utilize structures with holes and crevices (Glarou, Zrust, and Svendsen 2020).

Hammar Perry states that jacket foundations are already good fish hotels because of the complexity of the quadratic steel construction, and extra measures for fish are not necessary. For monopile it is great to have a scour protection, and design them to get as many structures and cavities as possible (Hammar Perry 2024, GU). Hemmingsson (2024, SwAM) mentions that in general, the greater diversity the better. She exemplifies with the fact that a straight steel pipe is not that appealing for organisms. If the structure is more diverse it can attract several different species. If algae establish themselves, followed by colonization of mussels, it attracts fish, which in turn attract birds diving for food. It also attracts seals and perhaps even porpoises. This sequence of events depends entirely on what the environment looks like from the beginning. Hemmingsson describes her experience of adaptations to enhance biodiversity. It is mainly related to choosing foundations and scour protections not based on what is cheapest, but instead based on local species and if they would benefit from certain designs (Hemmingsson 2024, SwAM).

5.8.2 Nature Inclusive Design

In the works of Hermans, Bos, and Prusina (2020) artificial reef structures called Nature Inclusive Design (NID) are presented, structures that can be placed in an offshore wind farm in order to enhance the artificial reef effect. They can be divided into different categories such as add-on units, standalone units (SA units), optimization of scour protection layer and optimization of cable protection layer (Hermans, Bos, and Prusina 2020). As this study does not focus on cables, optimization of cable protection layer will not be looked into further. The add-on units can be integrated on the foundation, for example mounted on a jacket foundation or a substation. They are unsuitable for monopile foundations since they cause difficulties in the construction phase. The focus will therefore be on add-on units for jacket foundations and substations, optimized scour protection layer and standalone units. All structures presented in 5.8.2 are described by Hermans, Bos, and Prusina (2020).

Add-on units

The first add-on unit is a Cod hotel which can be mounted on a jacket foundation or a substation. It consists of a cage-like structure, with tubes and funnels inside. An illustration of a structure similar to a Cod hotel can be seen in figure 5.3. It is made for the Atlantic cod, designed to give shelter and provide food. It is estimated that the structure can provide an increased biomass of 34 kg of cod each year. The cost is estimated to a total of 3,672€ per unit. Another similar add-on structure is the Biohut® that have two or three cages combined, and is mounted on a jacket foundation, substation, or used as a standalone unit. The suitable species are Atlantic cod, poor cod and their prey. It is estimated that it will be able to support the same increase of biomass as the Cod hotel. The cost is estimated to 3,179€ per unit.

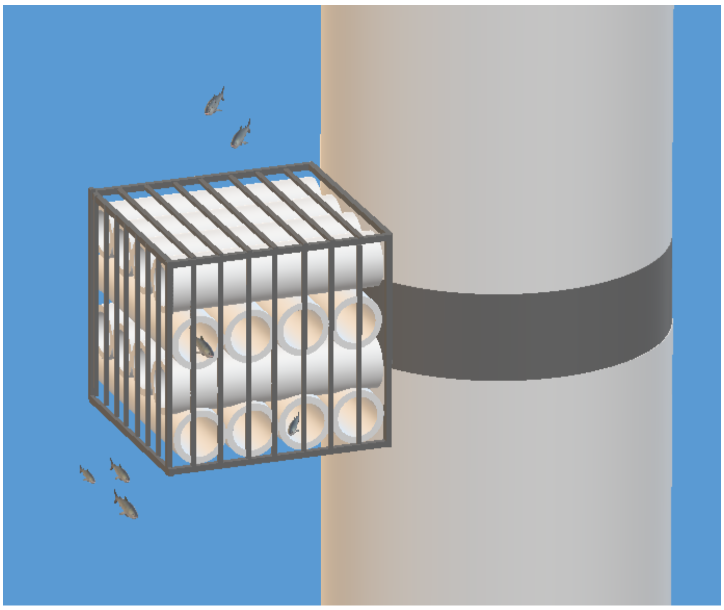

Figure 5.3: Illustration of a structure similar to a Cod hotel. Made in Paint3D.

Optimized scour protection layer

In the category optimized scour protection layer, measures such as an additional rock layer or an adapted grading armour layer can be added. The additional rock layer, which is placed on top of the filter and armour layers, can be seen in figure 5.4. The new layer should cover at least 20 percent of the scour protection and can include rocks with a variation of weights and sizes. They should be within a weight of 40–200 kg, dimension in between the rocks should be 10–30 cm and these crevices should be 20–50 cm deep. The new layer provides shelter for lobster, crab and cod. It can support lobster production of 0.82 kg per year and foundation. The cost of this measure is estimated to 19,079€ per scour protection. The adapted grading armour layer is only an alteration in the design of the original amour grading layer, with similar design to the additional rock layer, which makes the cost zero. It will have the same dimension restrictions for the rocks as the additional rock layer, and can support the same amount of biomass.

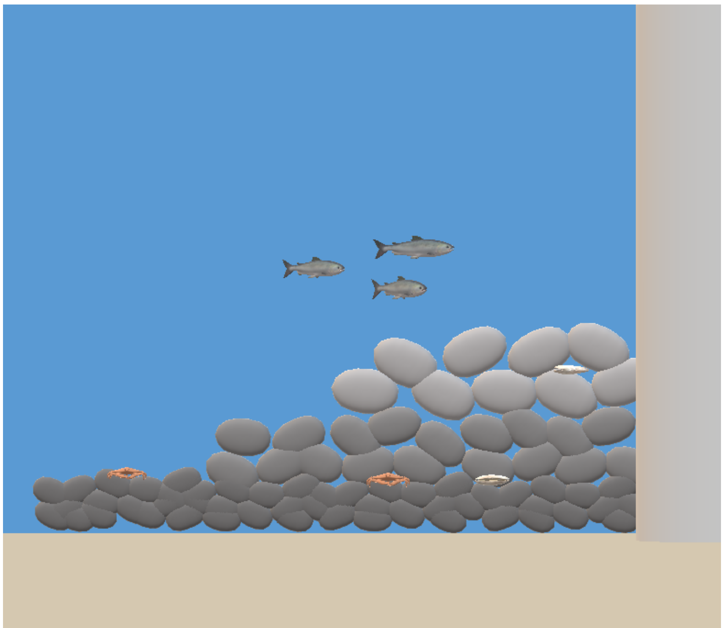

Figure 5.4: Illustration of a scour protection with an additional rock layer on top. Made in Paint3D.

Standalone units

The standalone units are artificial reef structures with different shapes and complexity, that are designed to benefit certain species. They are often placed on or in the scour protection layer. There are habitat pipes which consists of pipes made of steel with minimum four holes in, with dimensions between 15–30 cm. The habitat pipes should be 200 cm long and have a diameter of 100 cm and expected to cost 4,253€ per unit. *Fish hotel* (Design by *Wageningen University & Research, WUR*) is a similar structure but made with concrete. They are designed to promote cod and have a variety of holes in the structure. The fish hotel is expected to have a cost of 3,179€ per unit. There are also structures such as *Reefball®* and Layer cakes which are made of concrete and have a surface area of around 21 m^2. An illustration of a concrete structure similar to a *Reefball®* is presented in figure 5.5. They provide habitats for lobsters and crabs but also filtering species and fish. They are expected to have a total cost of 6,558€ per unit. *Reef cube®* have a cubic design, are made of concrete and are often placed in groups. The cubes usually come in the dimensions 50x50x50 cm. The cost for eight units is 6,296€ and it creates habitat for smaller species. 3D printed units can be in almost any shape and design and provides a complex habitat for multiple species based on the design. The cost is expected to be 8546€ per unit. *ECO armour block®* is a larger structure with the dimensions 120x120x120 cm with smaller holes aimed for small species. They have an estimated cost of 8,347€ per unit and are made with concrete, with an addition of 10 percent ECO admix which reduces the carbon footprint and strengthens the concrete. Oyster gabions consist of a large cage, filled with shells from oyster in order to promote the growth of the European flat oyster. The estimated cost is 9,340€ per unit. The *Biohut®* which was described above can also be used as a standalone unit and in that case it can support cod, lobster, and crab.

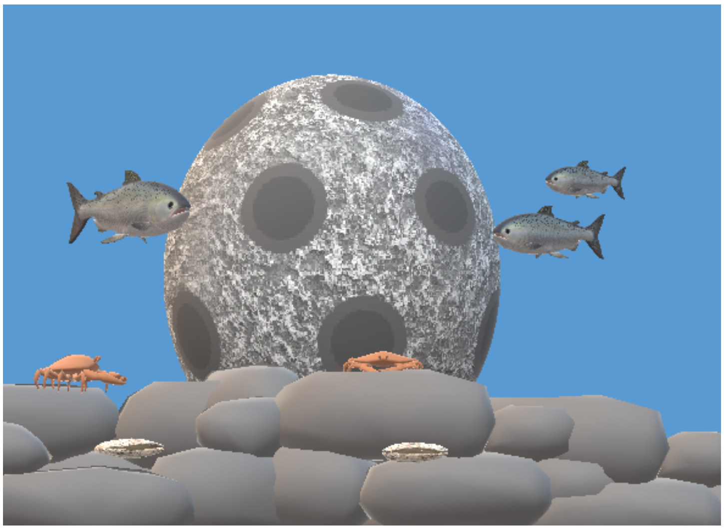

Figure 5.5: Illustration of a structure similar to a Reefball®. Made in Paint3D.

Table 5.2 presents a summary of the measures mentioned, along with their respective application and cost.

Table 5.2: Measures and their characteristics.

Category	**Measure**	**Application**	**Cost (€)**
Add-on unit	Cod hotel	Jacket, substation	3,672
	Biohut®		3,179
Optimized scour protection layer	Additional rock layer	Monopile, gravity	19,079
	Adapted grading armour layer		0
SA unit	Habitat pipes	Monopile, gravity, jacket	4,253
	Fish hotel (WUR)		3,179
	Reefball® and layer cakes		6,558
	Reef cube® (8 units)		6,296
	3D printed units		8,546
	ECO Armour Block®		8,347
	Oyster gabions		9,340
	Biohut®		3,179

It is important to consider what species should be enhanced, and then try to adapt solutions and measures in order to make it a suitable environment for those species (Koehler 2024, SLU Aqua). The measures and the species they promote are presented in table 5.3. This table can facilitate the choice of measures if the target species is among those listed.

Table 5.3: Measures and its supported species.

Measure	Atlantic cod	Poor cod	European lobster	Edible crab	European flat oyster
Biohut®	X	X			
Cod hotel	X	X			
Additional rock layer	X	X	X	X	X
Adapted grading armour layer	X (Juvenile)	X (Juvenile)	X (Juvenile)	X	X
Habitat pipes	X	X	X	X	
Fish hotel	X	X	X	X	
Reefball® and layer cakes	X	X	X	X	X
Reef cube®	X (Juvenile)	X (Juvenile)	X	X	X
3D printed units	X	X	X	X	X
ECO armour block	X (Juvenile)	X (Juvenile)	X (Juvenile)	X (Juvenile)	X
Oyster gabions	X (Juvenile)	X (Juvenile)	X (Juvenile)	X (Juvenile)	X
Biohut®	X	X	X (Juvenile)	X (Juvenile)	

A summary of all the different measures and applications, including protected area, which can be implemented to enhance positive biodiversity is presented in table 5.4 below.

Table 5.4: Measures to enhance positive effects.

Effect category	Measure	Outcome
Design of foundation and scour protection	Optimized scour protection Jacket foundation	More optimized hard bottom habitat Complex habitat
Nature Inclusive Design	Add-on units Optimized scour protection layer Stand-alone units	Habitat for cod Habitat for cod, lobster, crab, and oyster Habitat for cod, lobster, crab, and oyster
Protected area	Restricted from fishing	Chance for population growth

5.8.3 Practical implementation of artificial reefs in combination with wind power

When constructing an artificial reef, one of the aims is to maximise the efficiency. According to Glarou, Zrust, and Svendsen (2020) the efficiency, meaning the ability to support biodiversity and fish population, is determined by water depth, building material, level of complexity as well as the distance between the artificial structures. The former are described in section 5.8.1, while the latter will be described in more depth below.

To increase the productivity of the artificial reef it is important to take the foraging areas of the reef species into account. Making sure the areas are not overlapping for neighbouring reefs decreases the competition for food (Glarou, Zrust, and Svendsen 2020). To combat this issue when constructing artificial reefs Rosemond et al. (2018) suggested implementing buffer zones between the reefs. In their article they recommend a buffer zone of between 60 and 120 meters to account for 77 to 97 percent of the soft bottom feeding species around the reefs. This is somewhat in line with the findings of Baulaz et al. (2023) who state the reef effect stretches less than 100 meters away from the turbine. A distance of 120 meters is automatically fulfilled in a wind power plant, especially the present ones where the distance between the turbines is planned to be 1-2 km.

Each reef also has a carrying capacity, meaning the number of species and individuals that the artificial reef can support is limited. The carrying capacity partly depends on the size of the reef (Glarou, Zrust, and Svendsen 2020). According to Bohnsack and Sutherland (1985) the minimum effective artificial reef is 400 m^3 and the optimum recommended size is 800 to 1000 m^3. On the other hand, it has also been reported that the productivity increases directly with the size from 400 m^3 up to 4000 m^3 (Ogawa 1977 see Glarou, Zrust, and Svendsen 2020) As an example Rosemond et al. (2018) specifies that a scour protection with a diameter of 20 meters and thickness of 1.5 meters constitutes an artificial reef of the magnitude 471 m^3. This suggests that the scour protection constitutes an adequate artificial reef.

In their report, Fabi, Scarcella, and Spagnolo (2014) discussed aspects that are important to keep in mind before deciding on a location for an artificial reef. They highlight that both physical and chemical variables of the location such as depth, sediment type, currents, sedimentation rate, and waves should be considered. The stability of an artificial reef is dependent on the structural characteristics, the sediment type, the current intensity as well as the wave motion at the location. They exemplify with a combination of a muddy seabed and strong currents which can lead to sediment movements, causing scouring or sinking, which in turn can lead to displacement or destruction of the artificial structure. Additionally, waves and currents can lead to redistribution of sediment onto horizontal surfaces, forming a layer on the structure. This sediment can later be displaced by the same forces, meaning organisms that had settled in the sediment layer will be lost. Furthermore, Fabi, Scarcella, and Spagnolo (2014) emphasized that ecological features such as existing habitats, the life of the target species and connectivity should be taken into account. In short it means to avoid placement on already existing hard substrates or in sensitive habitats such as seagrass meadows, unless the aim is to restore damage. Also, if the structures are placed close to sensitive habitats a protective zone should be implemented to shield from any unintended disturbances (Lindberg and W. Seaman 2011).

6. Case study – West Wind

West Wind is a planned offshore wind farm by Eolus, outside of Gothenburg, more specifically outside the islands *Öckerkö* and *Hönö*. A map over the project area is shown in figure 6.1 and it is located in Skagerrak and in the northern part of Kattegat. It is partially situated in the economic zone, and partly in the territorial zone in the municipalities *Kungälv* and *Öckerö* (Andersson and Walfisz 2023).

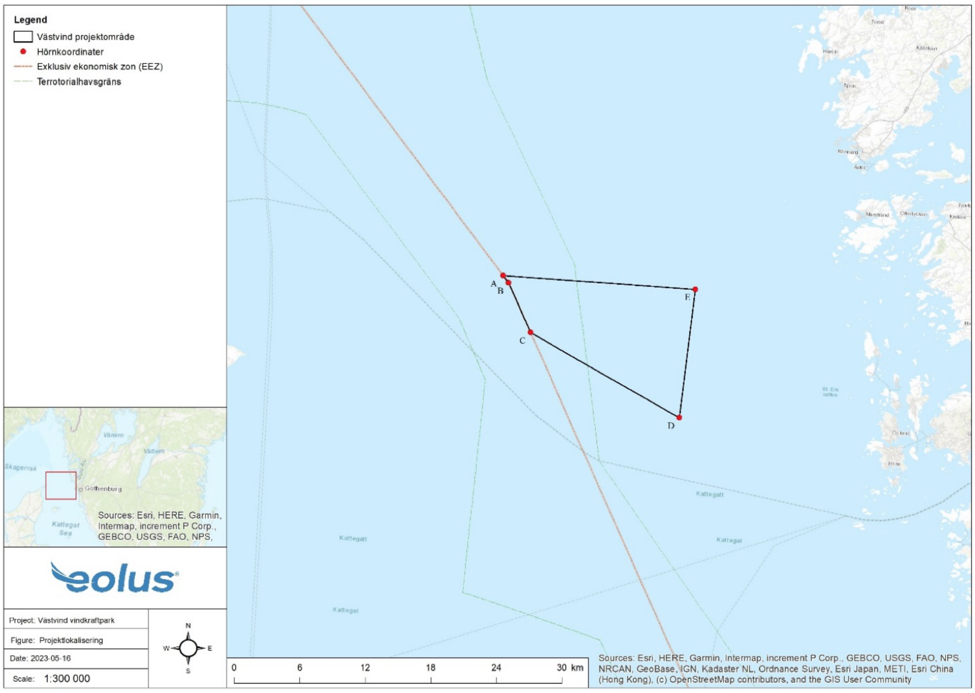

Figure 6.1: The location of the project area (Eolus 2023).

6.1 Technical description

The wind farm is planned to have a maximum of 50 wind turbines with a maximum height of 320 meters, on an area of 130 km^2. The depth of the project area varies between 30 and 100 meters. The installed capacity is planned to be 1,000 MW which would contribute to around 4-4.5 TWh electricity in a year (Andersson and Walfisz 2023). Each turbine is expected to have a capacity from 15 MW to over 20 MW. The foundations that are relevant to the project are either monopile foundations, jacket foundations or floating foundations. If monopile foundations are chosen, the pile is expected to have a diameter of 15 meters. If jacket foundations are used, the piles are significantly smaller, around 2-4 meters in diameter (Andersson and Walfisz 2023). The sediment in the project area was sampled and analysed for the EIA report. The result show surface sediments with predominately silt and elements of 20-47 percent sand. Low contents of clay particles were present, around 1-3 percent (Andersson and Walfisz 2023). Fine-grained particles can imply a soft seabed with low stability.

6.2 Relevant target species

The most common species that were found in the project area were cod species (*Gadidae*), mostly Atlantic cod (*Gadhus mohua*) and haddock (*Melanogrammus aeglefinus*). Other fish were flatfish species (*Pleuronectiformes*), mostly European plaice (*Pleuronectes platessa*) and common sole (*Solea solea*) as well as dragonets (*Callyonymus*). The most common crustacean species were swimming crab (*Liocarcinus sp*) and Norway lobster (*Nephrops norvegicus*). Stationary fauna that were found were bristle worm (*Polychaetes*), brittle stars (*Ophiurus*), sea urchins (*Brissopsis lyrifera*) and sea pens (*Virgularis mirabilis*). Close to the project area, there are areas where the abundance of the harbour porpoise (*Phocoena phocoena*) is high. Also the harbour seal (*Phoca vitulina*) is present and stable along the Swedish west coast and additionally there are some occurrences of grey seal (*Halichoerus grypu*) and other marine mammals (Andersson and Walfisz 2023).

There are not any habitats worthy of protection according to OSPAR, Art- och habitatdirektivet, the CAB, HELCOM and Artdatabanken within the project area (Andersson and Walfisz 2023). There is a type of habitat called *Sea pen seabeds with larger digging organisms* from the OSPAR list of threatened habitats. Even though there are sea pens in the project area, it is not classified as this type of habitat according to the CAB. However, east of the project area there is a valued area for sea pens, classified by the CAB (Andersson and Walfisz 2023). The species that are red-listed and classified as vulnerable from Artdatabanken is Atlantic cod and haddock. These species are scarce mainly because of bottom trawling and a lot of fishing. The environmental conditions in marine sediment seabeds can be classified in BQIm. The index showed that the conditions were *not good*, and the area has been exposed to a lot for bottom trawling. For cod, no spawning occurs within the project area, but can do so in nearby areas. Nevertheless, it is a nursing area for cod (Andersson and Walfisz 2023).

When consulting the interviewees about the area and the relevant target species, the focus seems to be mostly on fish and benthic species. Sköld (2024, SLU Aqua) explains that for example, depth is one variable that dictates what species are affected. If within the range of 40 to 90 meters it is generally crustaceans, such as the brown crab (*Cancer pagurus*). The Norway lobster (*Nephrops norvegicus*) lives in the soft seabed and digs holes (Sköld 2024, SLU Aqua), and can be of relevance in the area. There might also be valuable soft bottoms in this area according to Hemmingsson (2024, SwAM). Stora Middelgrund in Kattegat has some sensitive habitats. Even if the project is not inside or close to the Natura 2000 area there might still be valuable soft bottom species such as sea pens that can be affected. Some species might be red-listed and in that case, it is sensitive (Hemmingsson 2024, SwAM). Sköld states that in Kattegat, the cod stock collapsed a long time ago. Unfortunately, the conditions for the stock to recover are not very promising since there is still a lot of fishing with crayfish trawls that catch the cod. When new cod hatch, they disappear after a couple of years because they are taken as bycatch (Sköld 2024, SLU Aqua). For wind power in Kattegat an important aspect is often the cod spawning, according to Hemmingsson (2024, SwAM). She states that the cod population has been threatened and is still not doing well. It has therefore become a subject of many discussions for projects in this area (Hemmingsson 2024, SwAM).

Intensive commercial fishing takes place in the project area of West Wind with various methods. According to the investigation in the EIA report, in the surroundings of the project area the catch have mainly consisted of Atlantic herring (*Clupea harengus*), European sprat (*Sprattus sprattus*) and Norway lobster (*Nephrops norvegicus*). The catches in the project area have been dominated by Norway lobster. Previously, there have been large catches of Atlantic cod (*Gadus morhua*) but these have declined during the recent years. The Norway lobster have the highest commercial value of these species.

Based on the information presented above, some species were selected as target species for the case study. Atlantic cod is the main target species, because of decreasing populations and catches during recent years. It is also important for the ecosystem and can be seen as an umbrella species (Lengkeek et al. 2017). This means protecting the cod can benefit a wide range of other species. A commercially important species is the Norway lobster. Because of their sensitivity, it is also important to consider the sea pens and the marine mammals.

6.3 Estimated effects of West Wind

The relevant foundations chosen in the EIA because of the water depth are monopile, jacket and floating foundations. Floating foundations are not looked into further since they are outside the scope of this master thesis. In chapter 5, information on the impact of wind power plants on biodiversity was presented, along with interviewees' views on how the effects might change with larger wind power plants. This section with information regarding West Wind, compiled from Andersson and Walfisz (2023), serves as an example of how the impacts of larger wind power plants can be estimated. The effects from West Wind have been investigated by the project developer Eolus and their consultants, and presented in the EIA report written by Andersson and Walfisz (2023). The matrix in section 4.5.1 was used by Andersson and Walfisz (2023) to assess the effects and then establish consequences on impact categories. The effect categories chosen in this master thesis (underwater noise, seabed habitat loss, resuspension and settling of sediment, reef effect, indirect effects and cumulative effects) give consequences on the impact categories related to biodiversity in the EIA report (bottom habitats and bottom living animals, fish and crustaceans and marine mammals). These consequences are presented and summarized below. The effects and consequences are divided according to the life cycle phases of a wind power plant: installation, operation and decommissioning.

Underwater noise

The effects from underwater noise were investigated in the EIA report (Andersson and Walfisz 2023). For fish and crustaceans during the installation phase, a small consequence is expected. Low frequency underwater noise during the operational phase is expected to be very small. During decommissioning, similar consequences as during the installation phase are expected. For marine mammals, the seabed investigations will have a very small consequence on seal and porpoise. In the installation phase, if there will be piling, the consequences on seal and porpoises are expected to be small. Underwater noise from vessels will have a very small consequence. During the operational phase, low frequency noise will have insignificant consequences on marine mammals.

Seabed habitat loss

Using dimensions presented in Andersson and Walfisz (2023), examples of occupied seabed has been calculated. For monopile foundations, an area of the seabed will be occupied by the pile and the scour protection. With a pile of 15 meters in diameter and a scour protection with a width of 12.5 m, giving a total diameter of 40 m, the occupied seabed for one turbine is 1,257 m^2. See figure 6.2 below for an overview. For the whole wind farm with 50 turbines, this will be 62 850 m^2.

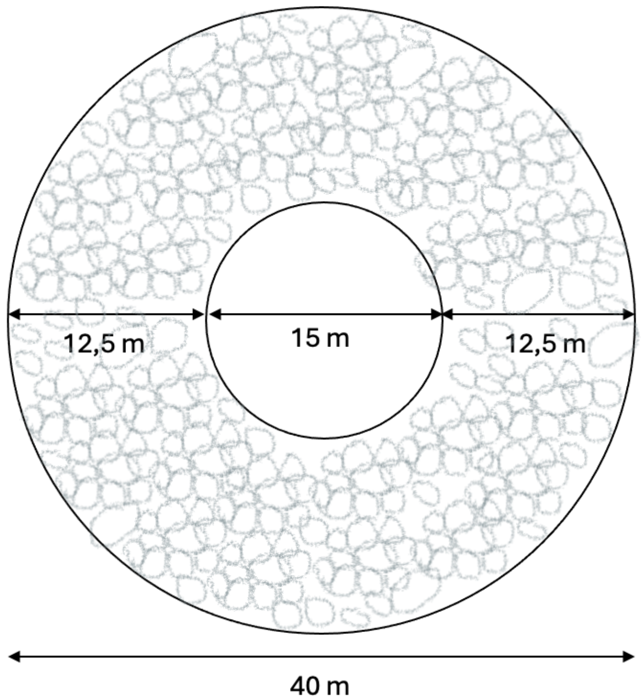

Figure 6.2: The occupation of seabed from a monopile foundation with a scour protection.

For jacket foundations a smaller part of the seabed will be occupied. The four piles have a diameter of 2-4 meters each, see figure 6.3 for an overview. A jacket with pile diameter of 3 meters would occupy an area of about 28 m^2 for one turbine, and 1,414 m^2 for the whole wind farm.

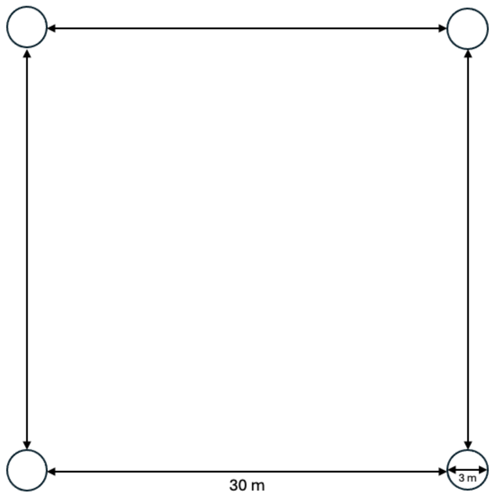

Figure 6.3: Jacket foundation dimensions.

Seen to the total project area of 130 km^2, the monopile foundation with scour protection will occupy about 0.05 percent and the jacket foundation about 0.0001 percent. Much due to this fact the loss of soft bottom habitat has been assessed to have very small consequence for bottom-dwelling species (Andersson and Walfisz 2023).

Resuspension and settling of sediment

A worst case scenario was calculated in the EIA report (Andersson and Walfisz 2023) where the foundations were to be installed with drilling. No effects are expected on Natura 2000 areas. Very small consequences are expected on bottom habitats and bottom living animals during the installation phase. Small consequences for fish and crustaceans during the installation phase are expected. There will be insignificant consequences on marine mammals during the installation phase.

Reef effect

Because of the introduced hard surface, there will be a reef effect which during the operational phase has a very small consequence on bottom habitats and bottom living animals. In the decommissioning phase, the consequence is expected to be moderate-large for the bottom habitats and bottom living animals if the hard substrates are removed. For fish and crustaceans in the installation phase the reef effect will give positive-insignificant consequences. For marine mammals the consequences will be insignificant for seal and porpoises. If the fish that benefit from the reef effect are food to the marine mammals, there can be a positive consequence for the marine mammals (Andersson and Walfisz 2023).

Indirect effects

Because of potentially avoided trawling, there could be positive consequences for bottom habitats and bottom living animals during the operational phase. For invasive species, the introduced hard surfaces will have a very small consequence during the operational phase. The potential spillover effect might lead to more fish and crustaceans if fishing is limited inside the project area. The total assessment of the consequences on commercial fishing, including more factors than the spillover effect, is that they can vary between positive and large negative (Andersson and Walfisz 2023).

Cumulative effects

Other planned wind farms close to West Wind are the Swedish wind farms Poseidon Nord and Mareld in the north and the Danish wind farm Fredrikshavn Nord southwest of West Wind. Poseidon Syd is overlapping with West Wind which means no cumulative effects can arise from these two since only one of them can be built. In a scenario where all wind farms are installed at the same time cumulative effects can arise. The information regarding cumulative effects is from Andersson and Walfisz (2023).

For bottom habitats and bottom living animals the cumulative effects in the installation phase from resuspension and settling of sediment are assessed as insignificant. In the operational phase, the consequences from additional hard substrate habitat are expected to be very small and local in each wind power plant. The cumulative effect of invasive species spreading is expected to have very small consequences on bottom habitats and bottom living animals. During the decommissioning phase, the risk of cumulative effects is expected to be insignificant to very small.

Fish and crustaceans can be affected by cumulative effects if the installation phase of West Wind coincides with the installation phase of Poseidon Nord. The cumulative effects would then have insignificant to small consequences. The cumulative effects could be underwater noise and higher concentrations of sediments over a larger area. In the operational phase, underwater noise from the wind power plants can affect fish and crustaceans by masking their communication or orientation signals in all planned wind power plants. The reef effect will arise in all planned wind power plants as well, causing the total area with a reef effect to be larger.

For marine mammals there can be cumulative effects if the installation phase of the planned wind power plants is at the same time. The cumulative effects from resuspension of sediment and underwater noise from vessels are expected to have insignificant consequences on marine mammals. During the operational phase the underwater noise from the wind power plants is assessed to have insignificant consequences on marine mammals. The reef effect from the introduced hard substrates will extend over a larger area if all planned wind power plants are built. It can lead to more fish, and this could lead to positive to insignificant consequences on marine mammals depending on the type of fish.

6.4 Propositions to minimise negative effects

In the following section measures aimed at minimising the negative effects (underwater noise, seabed habitat loss, resuspension and settling of sediment, indirect effects and cumulative effects) are discussed. Measures include those already proposed in the EIA report (Andersson and Walfisz 2023) as well as proposed additional measures out of those mentioned in section 5.7.

Underwater noise

The propositions in the EIA report for West Wind to minimise underwater noise is to use double bubble curtains when piling to reduce the noise levels for marine mammals. Hydrosound Damper will also be used to lower the noise levels from piling. Calculations on underwater noise levels were made in Andersson and Walfisz (2023) with the scenario that the monopile foundations of a diameter of 15 meters will be installed by piling. As an example, the sound exposure level for porpoises for one of the turbine positions is 166 SEL $_{24h,VHF}$ dB rel. 1 μ Pa^{2}s. This is one of the turbine positions giving rise to the highest SEL. With protective measures used such as Hydro Sound Damper and double bubble curtains, the value will be decreased to 139. This is below the porpoise levels for temporal threshold shift (TTS) which is 140, and permanent threshold shift (PTS) which is 155. In this scenario with the applied protective measures and the monopile foundations, porpoises must be in a distance of 250 meters from the piling noise in order to get a PTS from instantaneous noise peaks. Ramp up will also be used, and is a necessity for the machinery to work but also doubles as a method to scare away sensitive animals (Andersson and Walfisz 2023). To have a safer and more certain situation for marine mammals, the suggestion is to also include FaunaGuard as a measure to deter individual species before piling.

Seabed habitat loss

In terms of seabed habitat loss, the occupation of seabed and resulting loss of soft seabed habitat is inevitable. The loss of seabed is nonetheless smaller with jacket foundations than with monopile foundations along with scour protections. If only considering loss of soft seabed habitat, the jacket foundation is therefore favourable. On the other hand, it should be considered that new habitat, but of a different kind, is gained when a scour protection is used. To avoid sensitive habitats within the project area which might have been missed earlier, it is recommended that micrositing should be performed when deciding the specific locations for the foundations.

Resuspension and settling of sediment

Fish and crustaceans are expected to be affected the most from resuspension and settling of sediment, with consequences classified as small. The concentration of sediment in the water is expected to reach levels over 100 mg/l but for a small area and for a time period shorter than 14 days. As mentioned in section 5.3 this is not a defined limit and the sensitivity differs between species and life stages for fish. With regards to cod, it has been established that there will be no spawning in the area. However, there will likely be eggs and larvae present, most probably during the period March–April (Andersson and Walfisz 2023). Since egg and larvae are the most sensitive life stages for fish the recommendation is to avoid this time period if the aim is to benefit the cod stock. *Lektidsportalen* mentioned in section 5.7 was used for the EIA in order to find the time period with the highest combined sensitivity index. When this was done in 2020, April–July was the time period with the highest combined sensitivity index, peaking in May and July. When checking the current results in *Lektidsportalen* they differ slightly but the period with highest sensitivity index still matches. Combining this with the sensitive period for cod in the project area, the time period to avoid for the sake of fish and crustaceans should be March–July.

In the worst case scenario the sediment can spread 8.6 km from the activity (Andersson and Walfisz 2023). The valuable habitat for seapens located east of the project could be a cause for concern with regards to settlement of sediment on the seabed. The valuable habitat is located roughly 2 km from the closest part of the project area. However, the expected deposition of sediment at a distance of 1 km from the activity will be 1.6 centimetres and decrease with distance. According to Hill and Tyler-Walters (2018) the seapens can handle a deposition of about 5 centimetres of sediment. For that reason it will most likely not be necessary with any additional measures to limit the spreading of sediment. If extra caution is desired, one of the protective screens mentioned in section 5.7 could be utilized when installing the foundations in the southeast corner of the project area.

When it comes to the installation method of the foundations it is, as described in section 5.3, better with piling than drilling seen to the spreading of sediment. However, as mentioned in section 4.2.1, drilling is needed if impermeable materials are encountered during piling. It may therefore not be possible to opt out completely, but the recommendation in terms of limiting sediment spreading is to avoid drilling to the greatest extent possible.

Indirect effects

One indirect effect that can be considered negative is the risk of invasive species. This is hard to avoid but has only a very small consequence. The consequence on commercial fishing, including spillover effect, was hard to predict and depend heavily on the intention of coexistence from the project developers. If the aim is to restrict fishing inside the wind farm, there will be a protective area which is a positive effect for biodiversity, which can further contribute to the spillover effect. In the case of West Wind, the aim is to try to coexist with commercial fishing, which means that the important measures are communication, planning and appropriate design of the wind farm.

Cumulative effects

The highest risk for cumulative effects to arise are when the installation phases of the planned wind power plants overlap in time. To avoid cumulative effects, the most important measure is planning. If both Poseidon Nord and West Wind get permission to build, it is even more important to make sure that they are not installed at the same time, since they are situated closest to each other.

6.5 Propositions to enhance positive effects

In the following section the measures presented in chapter 5.8 are applied in the project design, with regard to the specific characteristics of the site. To do so the propositions are presented in four different layouts. The layouts show two locations within the project area, each with the two types of fixed foundations that are relevant. Different solutions are applicable depending on if jacket foundations or monopile foundations are chosen for the project, since their characteristics dictate what implementations are possible and relevant.

For monopile foundations, although the new substrate is of another nature, the scour protection will increase the surface area by approximately 2.5 times. This results in a net gain of surface habitat of 2,700 m^2 for one turbine, and 135,000 m^2 for the whole wind farm. The scour protection in itself is a good habitat for fauna, but a well thought out design of the scour protection would be beneficial, with for example additional rock layer and standalone units. This would increase the hard habitat area further and be beneficial for cod, lobster and crab. Adapting the graded armour layer, with suitable crevices between the rocks and blocks, could be advantageous. It should not constitute any extra costs while at the same time contributing to a better nursing habitat for cod, lobster and crab. On top of the scour protection, it would be beneficial to include standalone units such as several Reefball®, cod hotels or 3D printed units, in order to make the habitat even more complex and promote a more diverse habitat. The cost and habitat created would differ depending on the number of units. If three Reefball® were to be placed on each of the 50 scour protections, the cost would be about 1,000,000 € and contribute to 3,150 m^2 surface area.

The jacket structure will contribute with habitats for cod and other fish as well, on its own, with a variation of currents around the foundation. It could be beneficial to have add-on cod hotels together with standalone units on the seabed. This is to promote the Atlantic cod and possibly it would result in a spillover effect outside of the wind farm. If one add-on cod hotel unit would be placed on each turbine, it would cost 183,600 € for 50 turbines according to the estimated cost from Hermans, Bos, and Prusina (2020). There is of course the option of having fewer or more add-on units, depending on the budget of the project. The more artificial structures close together, the more connectivity the wind farm will have.

Figure 6.4: Water depth in the project area of West Wind.

There are different conditions in the wind farm project area. The deeper parts are situated in the north-east, with depth up to a 100 metres. Here, there are no plans to install any fixed foundations. In the middle and western part of the project area, the depths vary between 40 and 56 metres, see figure 6.4 for details. An example layout of the project area from the EIA report, including cables, can be seen in figure 6.5. To propose more specific layouts for the Nature Inclusive Design choices, two smaller areas with six turbines in each were chosen and will be referred to as A and B. Area A is situated in the middle of the project area and includes the substation. This area was chosen to utilize the substation for add-on units and to concentrate the reef community to the middle parts. When located in the middle, the connectivity between the foundations in the chosen area and the rest of the project area might be higher. A potential drawback with area A is that the fauna might be disturbed more frequently by maintenance vessels accessing the substation compared to the turbines. Area B is located in the northwest corner, in the shallowest parts of the project area. There are less cables in area B than area A which might be advantageous if there is an issue with placing structures near the cables. Area B is placed furthest away possible from the valuable area with seapens located southwest of the project area. This minimises the risk of damaging habitats for seapens when the hard bottom habitat is expanded and enhanced. These two areas would act as boosters for the reef effect and hopefully increase the spreading of species to the rest of the wind farm.

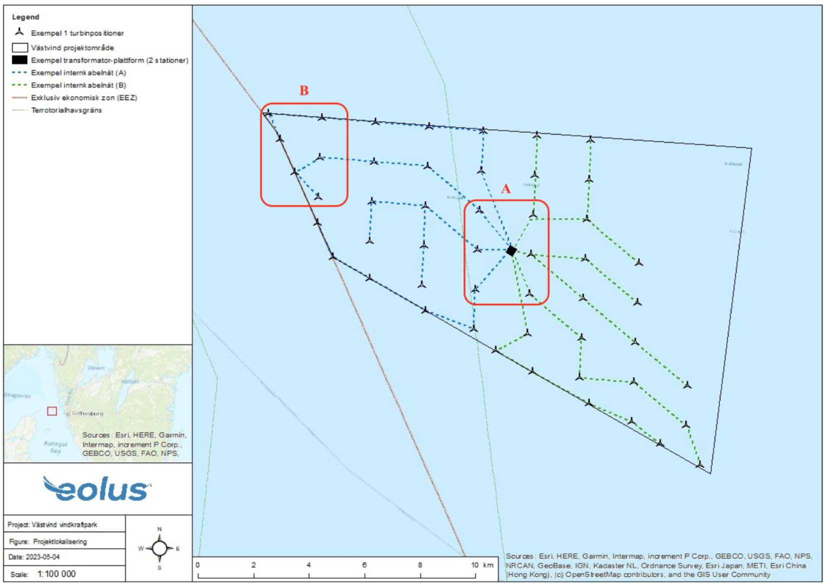

Figure 6.5: Areas A and B in the project area (Eolus 2024).

The local conditions with a soft seabed limits the potential ways of using the measures listed in table 5.2. As presented in chapter 5.8, the placement of such structures on a soft seabed can result in them being displaced or destroyed. With a distance of 1–2 km between the foundations it would be beneficial to place structures in between to increase the connectivity. However, since this is unfeasible for the location the SA units can be placed on top the scour protections and an alternative solution to achieve increased connectivity is to replace the structures with stone reefs. Stone reefs are simply units of stones in varying sizes placed on the seabed, similarly to a scour protection. If constructed in a similar way to a scour protection, the risk of the stone reefs sinking into the seabed, like the stand alone units (SA units) would, probably decreases.

According to Eolus, there will be a safety distance of 50 metres to all turbines in which it is not allowed to reside or pass through. Since the reef effect extends about 100 metres, a protective distance larger than 50 metres should be implemented to ensure a greater effect. The buffer zones mentioned in section 5.8.3 meant that foraging areas outside the reef should be taken into account. The buffer zones were suggested to be 60–120 metres from the edge of the reef. In this area, more fauna can be expected to occur and for that reason 50 metres of safety distance from the turbine is most likely not enough to act as protection for biodiversity. If the entire wind power plant would be a protected zone it would allow marine flora and fauna to thrive. However, since the project area largely overlaps with the national interest for commercial fishing this would be difficult to implement. Therefore, the proposal for some of the layouts is to make the particular area of the layout a small protected zone to get maximum effect from the installed measures. All layouts in area A include a suggested protected zone since the shorter distance between the turbines and the substation makes the area crowded and therefore less suitable for fishing. The two layouts with proposed stone reefs include a suggested protected zone to protect the structures, especially in case trawling is allowed within the wind power plant.

6.5.1 Layouts

The different layouts with proposed design of measures to enhance the environments for the target species are presented below. The layouts in area A are presented first, followed by the layouts in area B.

Layout 1

This first layout option presented in figure 6.6 is with monopile foundations, and is located in area A. Two add-on cod hotels are to be put on the substation. Each foundation should have scour protection optimization, by either adapted graded armour layer or additional rock layer. The cables near the substation can be buried in the seabed or covered with optimized cable protection. Although this can be beneficial, it is not included in the scope of this thesis. With the cod hotels as well as the adapted graded armour layer, both juvenile and adult cod are supported. The adapted graded armour layer will also function as a nursery for crabs and lobster. The stand alone units (SA units) for this layout are three Reefball®/layer cakes placed on the scour protection on each of the six turbines, to function as a shelter and nursery for cod, crab and lobster.

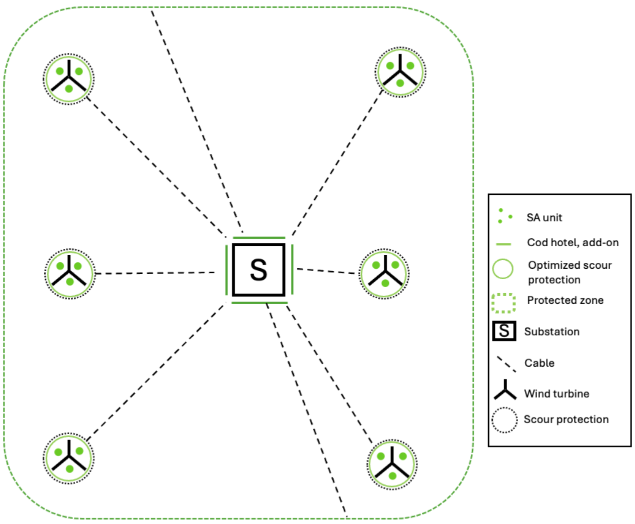

Figure 6.6: Layout 1 with monopile foundations.

Layout 2

Layout 2 is also in area A, with jacket foundations. Two options of this layout can be seen in figure 6.7 and 6.8. The jacket foundation already functions as a cod hotel, since it offers shelter for cod in the structure, and growth which can provide food. To enhance the habitat further, two add-on cod hotels are to be placed on the substation as well as one on each foundation. To increase connectivity between the turbines, two stone reefs can be placed on the seabed as seen in 6.7 . The other version of this layout, shown in figure 6.8 instead has the stone reef as a scour protection, around the foundation, which can be good if the seabed is very soft. This will provide habitat for adult cod. This layout also includes the proposed protected zone where fishing is not allowed.

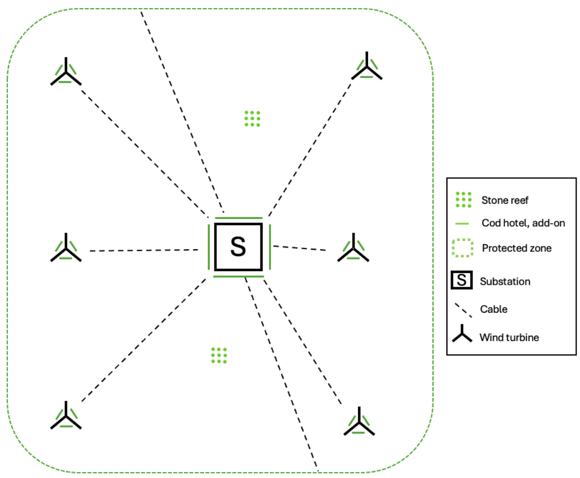

Figure 6.7: Layout 2.1 with jacket foundations.

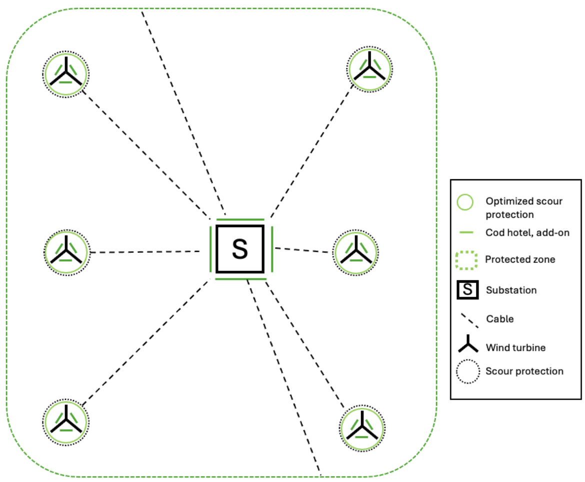

Figure 6.8: Layout 2.2 with jacket foundations.

Layout 3

In area B, in the top west corner of the project area, the third layout is located. It has monopile foundations and can be seen in figure 6.9. In this layout the scour protection is optimized with adapted graded armour layer. Standalone units in the form of Reefball®/layer cakes are placed on the scour protection to function as a shelter and nursery for cod, crab and lobster.

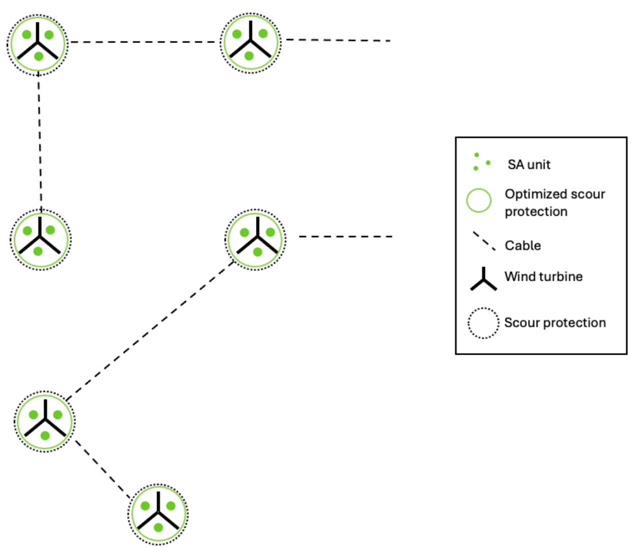

Figure 6.9: Layout 3 with monopile foundations.

Layout 4

The fourth layout is located in area B, and jacket foundations are used. This layout is also presented in two versions, see figure 6.10 and 6.11 below. Similarly as in layout 3, the jacket foundation will contribute to a complex habitat in itself. Add-on cod hotels are placed, one on each of the six jacket foundations, which will contribute to a nursery for juvenile cod and shelter for adult cod. A stone reef is placed in between the turbines for 6.10, in two different locations, to create a habitat for adult cod. In layout 6.11 the stone reef are placed around the foundations instead, resembling scour protections.

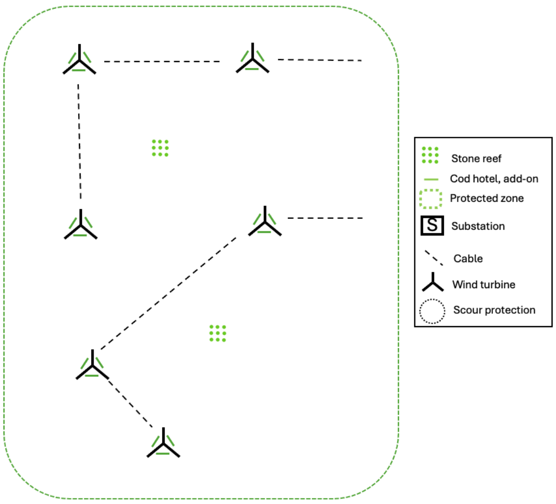

Figure 6.10: Layout 4.1 with jacket foundations.

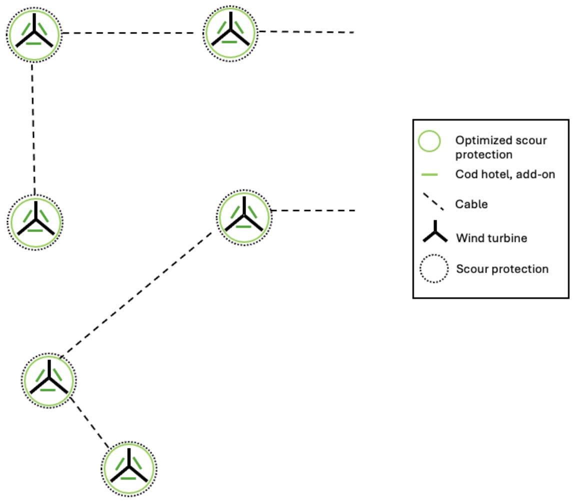

Figure 6.11: Layout 4.2 with jacket foundations.

6.6 Additional reflections

For the target species cod, lobster and crab, these layouts could result in an increase in the populations, potentially causing a spillover effect. This is a long-term perspective but could be beneficial for catch rates in the nearby area. Additionally, if the whole project area becomes a protected area, where fishing is not allowed, this would be the most beneficial for biodiversity. It could further increase the spillover effect and giving the trawl affected area a chance to restore. Although, this is not likely for West Wind, considering the coexistence with commercial fishing. If a larger number of NID structures were used in the project area, this would probably contribute to even larger positive effects.

The layouts have different foundations, design and measures to enhance positive biodiversity. The most suitable layout is very dependent on cost, fishing coexistence and of course target species. Regarding underwater noise and occupation of seabed jacket foundations will be the better option. For resuspension and settling of sediments, jacket foundations have a smaller impact than monopile. Both monopile and jacket foundation give rise to the reef effect. Monopile with scour protection mostly supports crustaceans and jackets are better for fish. In regard to the smallest negative effects and the target species being cod, jacket foundations would be a better choice. The layouts with jacket foundations are layouts 2 and 4.

The most suitable area to create a hotspot for biodiversity would be area A, in the middle of the wind farm, since there are more structures to implement NID structures on, and this will give rise to a closer connected artificial reef area. For layout 2, there are two different versions. There is one layout where there are stone reefs placed in between the turbines, and one where there are scour protections around the foundations. If scour protections are necessary, depending on the geological conditions, that would be the most suitable version. This would also be a suitable version if fishing will be allowed in the whole project area, and a protected zone around area A is not a possibility. If a protected area is possible this also indicates that the stone reefs can be placed without the risk of fishing gear getting stuck. This means that layout 2.1 would be the most advantageous for biodiversity, both giving rise to a protected zone as well as measures for enhancement of habitat for cod. The protected zone will be beneficial for Norway lobster, whose habitat is the soft seabed. The stone reefs will create additional habitat for crab.

It would be ideal if cod hotels could also be used for monopiles. They are in greater need of added complexity than jacket foundations due to the plain and straight surface of the pile. However, according to Hermans, Bos, and Prusina (2020) there is a limitation to using cod hotels for monopiles due to issues attaching the structure to the pile. It cannot be attached before piling as the piling process risks damaging the cod hotel, while attaching it after the piling requires underwater welding which poses logistical difficulties (Hermans, Bos, and Prusina 2020). However, a possible alternative attachment solution might be to weld the cod hotel to a metal band, big enough to encircle the pile. This attachment style could look something like what can be seen in figure 5.3 included in section 5.8.2. If the closing mechanism of the band does not require welding the need for underwater welding is eliminated. Ideally, the installation method of the cod hotel would allow for partial mounting above the surface, followed by submersion to the desired depth where the metal band is tightened. With a solution like this the cod hotel would be applicable for monopiles as well. Hopefully this issue will be resolved in the near future.

Hammar Perry (2024, GU) explains that at present, Kattegat is very flat, with only small elements of rock in large clay plains. A hundred years ago, there were a lot of haploop habitats, which were created by small crustaceans. Trawling has flattened out the seabed, and stone fishing has removed the stones that were scattered on the bottom. Hammar Perry believes it restores a type of natural reef occurrence if a wind power plant is built in Kattegat. This information further establishes the positive impact from added wind turbines and artificial reefs in Kattegat.

When decommissioning the wind farm, it is very important to consider the created artificial reefs. The stone reefs, scour protection or the standalone units should be left at the seabed, if monitoring shows a long-term positive effect. The layouts presented only include six foundations and and in the perspective of the entire power plant, and especially Skagerrak and Kattegat, this is a very small part. Nonetheless, it could be a good contribution to the work with monitoring and researching the effect from NID, with the aim of hopefully incorporating more solutions to enhance biodiversity in the future.

7. Analysis of interview study

In this section, an analysis of the topics identified in the interview study is presented. The views from the experts, the County Administrative Boards as well as from the Swedish Agency for Marine and Water Management are compiled.

7.1 Role of NID in the permitting process

Whether NID could be an advantage in the permitting process is discussed in the interviews. Even if the CABs are not the final decision makers, they prepare the case and give a proposal to the government for projects in the economic zone, and their thoughts are therefore valued. The experts are also asked about if NID could bring an advantage to see if the views differ between the CABs and the experts. The opinions from SwAM, as a referral authority, are also interesting since they give an additional point of view. The overarching answer is that other factors are of greater significance and that a positive effect from NID has to be proven with science-based support in order for them to become an advantage. Overall, the CABs are more cautious around NID as an advantage compared to the experts.

The views of the experts on the advantage in the permitting process differ slightly. Koehler at SLU Aqua thinks that it could be an advantage in a permitting process if NID was included in a wind power project to enhance biodiversity. It will definitely be weighed in if there is science-based support for NID (Koehler 2024, SLU Aqua). Hammar Perry at the University of Gothenburg believes that today, it will probably not be easier to get a permit for a wind farm with included measures for enhanced positive effects on biodiversity. However, it is possible that this changes in the future (Hammar Perry 2024, GU). Sköld at SLU Aqua mentioned that there most likely are other trade-offs of greater importance than if the project includes NID that promote artificial reefs. As examples he highlights factors such as uncertainties about how the wind farm itself affects organisms as well as alternative industries. Sköld (2024, SLU Aqua) suggested that NID might not play a big role in the outcome but could perhaps become a condition in a permitting process.

The opinions from the CABs are mostly united. They believe that other factors than NID usually are deciding whether a wind farm will get a permit or not. Additionally, the potential positive effects from NID must be proven before it can contribute to an advantage in the permitting process. Smith from the CAB *Blekinge* thinks extra positive measures would be taken into consideration if they were to be included in the application. However, she points out that if nothing similar has been done before there are large uncertainties of whether they would work or not. Some advantage might be possible, but she mentions that the permitting process is more heavily reliant on what investigations that have been made that support the project, what protective measures that are undertaken and how well motivated the application is. Smith states that biodiversity as a question is very included in the permitting process today. Nationally, many lessons can be learned from other international projects, which makes it possible that extra positive measures can be included even more in the permitting process in Sweden. Additionally, if the operators get an advantage in the permitting process, they will probably use positive measures more (Smith 2024, CAB B).

Olsson from the CAB *Halland* points out that according to the Environmental Code, the wind farm must be admissible without compensation measures. Nonetheless, nothing hinders the companies from introducing positive measures anyway, but the company must show that the measures really are positive in order for them to become an advantage. To get a permit, there will probably not be any requirements to perform extra positive measures, only protective measures. Olsson says that it is also a question about economy and whether companies can afford to include measures they are not obliged to. Additionally, there is often a general requirement that the project shall mostly be conducted according to what the application states. In an evaluation the focus is usually on what the largest risks are, and what will have the largest effect and then what permit conditions and protective measures that are needed (Olsson 2024, CAB H). Toivio and Stenegren from the CAB *Västra Götaland* also state that the wind farm must be admissible first, and then potential compensation measures or positive measures might be considered. There are complex ecosystems with unique values, which means that placing an artificial reef might not contribute to the same values as a natural reef. According to Toivio and Stenegren (2024, CAB VG), if the positive effects on biodiversity are confirmed they would be taken into consideration in the permitting process. The risks that come with hard substrates, such as invasive species, must be considered as well. They point out that it is very important to first consider the target species and the natural values that exist at the site, and then design the solutions accordingly. Choosing the right location first and taking the steps as they come in the mitigation hierarchy is very important (Toivio and Stenegren 2024, CAB VG).

Hemmingsson from SwAM was also asked about advantages from NID in the permitting process and she thinks it could potentially be an advantage to include NID (Hemmingsson 2024, SwAM). However, she clearly points out that it could niether mitigate an unsuitable location nor compensate for potential damage. Instead, it can be used as an additional positive effect for a project in an already suitable area. Hemmingsson (2024, SwAM) continues, saying that if these measures would be considered necessary by the reviewing authority it may become a permit condition for the farm to include NID or similar, regardless of whether the company has brought up the idea or not. SwAM could make such a suggestion but currently this is unusual. Nevertheless, it is possible that a point is reached where these measures should become permit conditions in the future (Hemmingsson 2024, SwAM).

When asked about the role of NID in a case when two projects are competing for the same area, Hemmingsson (2024, SwAM) has the opinion that the addition of NID will most likely not be the deciding factor. This particular situation has occurred but SwAM were not in charge of giving the permit. In this case both companies got permission for a part of the area each, but proposals for a positive impact on biodiversity were not considered in the assessment. Instead, larger factors and overall assessments of the projects were taken into account. In addition to this Hemmingsson (2024, SwAM) states that the government wants to give permission to projects that can be realized within a fairly short time and so they are more interested in the companies and their financial resources to realize the project (Hemmingsson 2024, SwAM).

7.1.1 Valuing biodiversity

Depending on the view of increased biodiversity at a location, the reef effect can be considered both positive and negative. Therefore, the valuation of biodiversity affects the role of NID in the permitting process. Overall, the interviewees agree that the valuation of increased biodiversity is closely connected to the existing values of the location.

When a foundation is placed on a soft seabed, hard substrates are introduced which means there is a change of the environment at the location. According to Hemmingsson (2024, SwAM), increasing the occurrence of hard bottom elements in a soft bottom environment can be perfectly fine in some areas, while it should be avoided in other areas. She exemplifies with a special case of a wind power plant located in a Natura 2000 area. The conservation goals in the Natura 2000 area concern shoals and if hard elements are introduced, the natural system changes. In that scenario it was unfavourable, but if an area is unprotected and not in a designated Natura 2000 habitat, the effect from introducing hard substrates is less significant. Instead, it could potentially be positive, but this depends on what species in the area that are of interest to protect or benefit (Hemmingsson 2024, SwAM).

Hammar Perry's opinion is that higher connectivity resulting from NID is positive and increases the reef effect, which can even decrease eutrophication when filtrating organisms take up nutrients. He describes that the CAB or the government do not always want the environment to change more than necessary and introducing NID is not always in line with the objective. Hammar Perry also brings up the example of a Natura 2000 area, in which the natural environments shall be preserved. He states that if the natural environment in the Natura 2000 area is soft seabed, this would mean NID structures are not favourable. If new reef structures are proposed in such areas, he thinks it can be harder to get a permit (Hammar Perry 2024, GU). On the other hand, Hammar Perry (2024, GU) adds that the trend gravitates towards the realization that we must enhance biodiversity overall, especially in the ocean. He says this might indicate it will be easier to see NID as positive in the future, even in such areas.

In line with what Hammar Perry describes about the CABs, they stress the importance of knowing the present condition and value of a location and that it might be lost if changes to the natural environment occurs. Toivio and Stenegren (2024, CAB VG) highlight that when introducing hard substrates into a soft bottom area, the form of biodiversity that was present is removed. This will benefit some species, but the natural environment needs to be considered as well. They emphasize the importance of having an objective to what is desirable to restore or enhance. Additionally, it is important to know what values are important for this area and for which species a measure will have a positive effect (Toivio and Stenegren 2024, CAB VG). Olsson (2024, CAB H) mentions that when introducing measures intended for enhancing biodiversity, it is hard to know what will have a positive effect and what could be seen as a risk. If extra measures to increase the already existing reef effects are taken, there could be an increase of species. She goes on to say this can be seen as positive, but there could also be new species introduced to the ecosystem which poses a risk of elimination for old species.

7.1.2 Ecological compensation

In this master thesis NID is classified as positive enhancement of biodiversity, separate from the negative impact on biodiversity, hence not as compensation measure. This is because compensation is the last step in the mitigation hierarchy and should be avoided as far as possible, as written in section 2.2. The aim with NID is to contribute to an even better wind farm project, enhancing the biodiversity in the area. The views from the interviewees on classifying NID differ, but they agree that compensation should be done with caution and as a last step.

Hammar Perry states that compensation is about restoring something that you or someone else has destroyed. He means that measures aimed for enhancing positive effects on biodiversity is not a compensation measure, but rather an enhancement of the natural systems and the ecosystem services. A compensation measure is for example when an eelgrass meadow is dredged and then compensated by planting eelgrass in another place (Hammar Perry 2024, GU). Hemmingson's (2024, SwAM) opinion differs slightly since she thinks that NID could perhaps be seen as somewhat of a compensatory measure for the small inevitable negative impacts during the construction phase, such as sediment spreading. Toivio and Stenegren (2024, CAB VG) state that when compensating and restoring something, you should be aware of the complex and unique values that exist in ecosystems, and that it is not easy to replace something. The well-being of the soft bottom communities is varying, because of trawling and other activities, but they still have some value. It is hard to view it as a compensation measure if you change the habitat from soft seabed to hard seabed (Toivio and Stenegren 2024, CAB VG).

Compensatory measures are taken into consideration in the assessment of an EIA application, but they are not the main focus since it is a last step in the mitigation hierarchy. A few different perspectives on this topic were presented by Hemmingsson and Sköld. Hemmingsson describes the mitigation hierarchy and that the damage should first be avoided and reduced with protective measures. After that there might be remaining damage, and this can be compensated for. This means that compensation is not something that the SwAM looks at in the first stage when reviewing the applications. Still, it can be kept in mind for the overall assessment that compensation could yield long-term positive outcomes (Hemmingsson 2024, SwAM). Sköld's perception is that, in the context of NID being viewed as a way of compensating for issues not directly caused by the project, it may not be the primary concern in the assessment of a project application. Sköld also mentions the mitigation hierarchy, where in the first instance, the negative impact should be avoided, or in any case minimized. If the negative impact is so vast that it prompts compensatory measures, it suggests that the project has progressed too far in an unfavourable direction. For that reason, Sköld (2024, SLU Aqua) states that it could be considered as some form of greenwashing when attempting to solve a separate issue and use it to advocate for the project. As an example of such an issue he mentions implementing additional structures with the claim it will restore fish stocks when the cause of the issue is not the wind power plant but instead overfishing.

7.2 Coexistence with fishery

A discussion that often arises in connection with offshore wind power is its coexistence with the fishing industry. The interviewees are asked about the possibility of coexistence and potential influencing factors. The overarching viewpoint is that it can be difficult to combine wind power with all types of fishing but that certain options are more compatible than others.

Koehler (2024, SLU Aqua) mentions that some countries are working on combining the fishing industry with wind power plants, by allowing them to use certain tools and granting permission for them to access the area. There are restrictions for fishing in wind farms, such as buffer zones, and fishermen tend to avoid doing so. It can be expensive if they happen to damage a cable or collide with the towers, and some fishermen cannot afford adequate insurance. Because of the associated risks, they might move to another area nearby, which could be more sensitive to fishing, for example a Natura 2000 area (Koehler 2024, SLU Aqua).

Hemmingsson (2024, SwAM) believes not all types of fishing will be able to coexist with wind power. She describes that certain types of trawls, especially the very long pelagic trawls, are difficult to use in wind power plants with fixed foundations. Furthermore, Hemmingsson (2024, SwAM) mentions that in the case of floating foundations, almost no trawling will be possible but that some types of fishing using fixed gear such as cages and nets might be possible. According to Olsson (2024, CAB H), fishing organisations often oppose wind farms since it affects the ability to trawl. There is a national interest for commercial fishing, just like there are national interests for nature conservation and defence facilities. The government is responsible for monitoring the national interest of commercial fishing to ensure the effect is not too extensive, but it is a complex matter. There could be a need to develop new fishing methods for the national interest to not be affected as much. There are often terms in permits for wind farms that the wind farm owners shall set aside economic resources to develop new fishing methods in cooperation with the fishing organizations (Olsson 2024, CAB H). Koehler (2024, SLU Aqua) believes that one of the most important measure to be able to create coexistence between wind power and the fishing industry is communication, between all parties in an early stage. This is crucial to avoid some actors feeling left out. Early involvement in planning processes, and research such as development of fishing gear that may be suitable to use in wind farms are also important (Koehler 2024, SLU Aqua).

7.2.1 Spillover effect

Factors that can affect the coexistence with fishing include if the wind farm area is used as a protected area or a potential spillover effect. A protected area would contribute to a possibility for the ecosystem to recover in the area, if it was affected by, for example, intense bottom trawling. Hammar Perry (2024, GU) believes that more protected areas are necessary in general, including wind farms as protected areas. According to Koehler (2024, SLU Aqua), it could be possible to combine wind power with Natura 2000 areas, depending on the conservation plan and the objectives with the area. That needs to be assessed and evaluated for the specific site conditions (Koehler 2024, SLU Aqua). The spillover effect could contribute with an increased survival of fish that spreads outside of the farm, which would further be enhanced if the area was protected from fishing. If proven, the spillover effect could increase the acceptance of wind power plants. NID and other design choices could enhance the reef effect that wind farms naturally have, and perhaps contribute to an even larger spillover effect. The long-term spillover effects are not established, but the opinions from the interviewees are hopeful.

Regarding the spillover effect, Sköld (2024, SLU Aqua) states that the hope is for this phenomenon to occur while at the same time emphasizing that it is a long-term perspective. He mentions that many of the fish stocks are overfished which means that for them to recover there is a need for the age structures of the fish to be rebuilt and this will take a long time. However, the chance of fish stocks recovering increases with increased protection along with reduced fishing so from the perspective of biology there is potential. It is a long-term perspective which could lead to a better future. Sköld (2024, SLU Aqua) also highlights the difficulty of selling this idea to today's fishermen. Koehler is more hopeful, saying that if more studies quantify spillover effects for different marine species, then the fishing industry might have a more positive attitude (Koehler 2024, SLU Aqua). According to Hammar Perry (2024, GU), for fishermen to benefit from the spillover effect, the reproduction must be favoured at such a level that it becomes a net plus of fish. Hammar Perry states that for stationary fish such as cod, which is stationary during parts of the year, or lobster and benthic fauna, the spillover effect is verified as very large. There are examples where lobster have been observed in a Marine Protected Area where it has been noticed that the fishing of lobster outside the area is much better. The reproduction is ten times larger compared to other areas of lobster fishing (Hammar Perry 2024, GU).

There is fishing in very large areas of *Västerhavet* and Hammar Perry (2024, GU) mentions that professional fishermen often say that it will be impossible to earn a living with wind farms everywhere. Hammar Perry questions this, since it is often possible to fish to some extent in wind farms, depending on the local conditions and the design of the wind farm. Even if the available fishing area is decreased because of wind farms, this does not automatically mean that the catch will be less in a long-term perspective. According to Hammar Perry, the fish from the wind farms will spill over to the edges of the area (Hammar Perry 2024, GU).

7.3 Future prospects

The balance between having a fast approval time for wind farms to get fossil free energy fast, and at the same time keep doing detailed investigations on the effects on biodiversity is difficult to find, which the interviewees agree on. NID will probably be integrated more in wind farm projects in the future, while at the same time extensive research is needed to close the current knowledge gaps.

Sköld (2024, SLU Aqua) mentioned that it may seem unnecessary to spend vast amounts of money on conducting surveys and EIAs only to find that a location is not relevant. At the same time, there might be an upside to the time-consuming process. Permitting processes for wind farms have been going on for quite some time, allowing opportunity for significant technical advancement. However, it is somewhat concerning that the process is so slow. If the aim is to mitigate climate change the process of switching to sustainable energy sources must be quick (Sköld 2024, SLU Aqua). Koehler (2024, SLU Aqua) also points out that renewable energy is needed for the sake of the climate but that it is also important the environmental effects are tested thoroughly since the wind turbines will remain in place for several decades. It is a compromise between not taking too long and the need to investigate carefully (Koehler 2024, SLU Aqua).

According to Hemmingsson (2024, SwAM) it is possible that NID become a part of the permitting process. The current obstacle for the SwAM is that they are uncertain about what it would mean and what it would look like. It is quite new and has not been included in the process yet but there is every possibility that it will. The SwAM has seen proposals for conditions that have never been seen before so anything is possible. Even if NID is not part of the permitting process yet, Hemmingsson mentions that she has seen NID in some applications. So far, they are usually not described in much detail. The descriptions are quite vague and mostly concerns the company looking into these types of solutions (Hemmingsson 2024, SwAM).

There is a lack of knowledge about long-term effects of wind power plants on marine flora and fauna. To gain this type of information Hemmingsson (2024, SwAM) states that long-term studies must be performed. Such studies require that a wind power plant of today's planned size is built and that proper control programs are developed. The programs should include measurements and ongoing monitoring of animal behaviour connected to all possible environmental aspects but especially from underwater noise (Hemmingsson 2024, SwAM). Toivio and Stenegren (2024, CAB VG) also specifies that more knowledge about the values and biodiversity in the ocean, and how it might be affected, is needed. They emphasise that joint studies and control programs would be good to get better comparable data. The increased knowledge from studies and control programs could lead to biodiversity playing an even bigger role in the permitting process in the future. Toivio and Stenegren (2024, CAB VG) also suggest that companies could contribute with a lot of this knowledge needed by taking responsibility to coordinate these investigations.

Sköld's (2024, SLU Aqua) opinion as a biologist is that if an expansion of offshore wind power on a large scale is to take place, it is of utmost importance that it is done step by step and that very careful follow-up is carried out. Much because of the potential cumulative effects it may have on large migration routes for fish and birds. It is difficult to say whether the outcome will be positive or negative and from that perspective, it is gradual caution and good control programs that are needed to avoid underestimating the impact. He mentions that a comparison could be made to the very rapid expansion of hydropower in Sweden when the country was industrialized. It has led to such terrible destruction of nature through the claiming of so much land, and land that has been put under water. It has changed large parts of Sweden's landscape, but to the greatest extent in northern Sweden, where the large rivers are located. It has also affected biodiversity substantially, especially when it comes to migratory fish but also other species. He does not think the situation is the same with wind power, but it is an example of why the expansion should be done with caution (Sköld 2024, SLU Aqua).

Hemmingsson (2024, SwAM) explains that SwaM assesses each wind power plant individually but that they also attempt to consider what might be built nearby and whether the combined impact would be greater. However, they are not able to make a final assessment of the cumulative effects since they do not have access to an overview plan. Instead, a message is conveyed to the government concerning the cumulative assessment along with the assessment of the individual farm. The cumulative effects cannot be finalized until it is known what other wind farms will get a permit. Hemmingsson mentions that for this reason it would be beneficial to have a system commencing from how much of each sea basin can be occupied, followed by the selection of a suitable area. Hemmingsson states that as it is today, the cumulative assessments are getting very disorganized. She goes on to say that it is also difficult for the wind power developers since they do not know which wind farms are to be realized and therefore not which ones to include in their cumulative assessment. Some companies include everything, even projects in an early stage, and others only include permitted projects (Hemmingsson 2024, SwAM).

7.3.1 Future permitting process

There are lengthy processes for offshore wind power permits, with issues regarding competing interests for overlapping areas. There is an ongoing governmental investigation to see how it can be made more efficient. Additionally, the investigation will explore if a system where the government points out designated areas suitable for wind power development could be possible to implement in the future in Sweden. The interviewees have different opinions on if the implementation could be possible and if it would be beneficial, including the possibility to implement NID more in this type of system.

Olsson (2024, CAB H) says that other countries such as Denmark, Germany, Great Britain and the Netherlands plan their seas much more than Sweden. Areas suitable for wind power is pointed out by the government. In Sweden there are Marine Spatial plans, but they are not directorial and they only show where the national interests are. This makes anticipating cumulative effects much harder. Olsson thinks Sweden would benefit from a system with more planning. There is an ongoing investigation on how the legislation around the evaluation of offshore wind power looks like today, which the government identified was needed (Olsson 2024, CAB H). Hemmingsson (2024, SwAM) states that SwAM has previously carried out an investigation to make the permitting process more efficient. Hemmingsson also mentioned the investigation issued by the government which is underway to examine how the permitting process for offshore wind power can become more efficient. One of the proposals in this investigation is reminiscent of an auction-based system. The timeline is uncertain, and a change of system would most likely require significant legislative changes. There is no certainty that a change like this would be made but the proposal has been raised and it would make the process easier (Hemmingsson 2024, SwAM).

In other countries than Sweden, there are systems where the government points out suitable areas for offshore wind power and assign them depending on different criteria. This type of system will be referred to as an *auction-based system*, which the interviewees were asked about. Hemmingsson (2024, SwAM) expresses that in her opinion the auction-based systems that exist in other countries are good. The Swedish system becomes very tricky since several operators can apply for overlapping areas until there is a permit. This leads to heavily burdened authorities, and it is simply not efficient in terms of resources and authorities (Hemmingsson 2024, SwAM). Hammar Perry (2024, GU) thinks that it would be very beneficial if there would be an auction-based system introduced in Sweden, where the government points out areas suitable for wind power. This would be more efficient since there are many granted permits that are not being used today (Hammar Perry 2024, GU).

Smith (2024, CAB B) points out that because the decision is made nationally, it is hard to predict if an auction-based system will be introduced in Sweden in the future. Other countries have this system and therefore it is more probable that Sweden will introduce it as well. It would be beneficial for the project developers, with considerably less uncertainty (Smith 2024, CAB B). Sköld (2024, SLU Aqua) expresses that from a rational standpoint it would be preferable to have a basic plan instead of searching for a suitable location everywhere. Toivio and Stenegren (2024, CAB VG) state that the planned development of offshore wind power is well underway. This means that many of the suitable areas already are claimed, which makes it difficult to implement an auction-based system now. They believe that the assigned investigation is needed, but it should have been done several years ago and not now when the wind farms are starting to get permits in the current system (Toivio and Stenegren 2024, CAB VG).

The interviewees agree that there are possibilities to include criteria to enhance biodiversity when implementing an auction-based system. Koehler (2024, SLU Aqua) describes that in the Netherlands, companies are imposed to describe their actions regarding enhancing the natural ecosystem (Koehler and Bergström 2023). She believes this could become a future requirement in Sweden, but that the Netherlands are at the forefront in these questions. Koehler explains that this is because they have smaller areas to build offshore wind power in, which is why they have encountered these conflicts earlier. Hemmingsson (2024, SwAM) stated that in an auction-based system, it might be possible to have "positive impact on biodiversity" as a requirement. In that case there might be some kind of tendering process where the companies must report how they work and what criteria they work according to. If so, the work with Nature Inclusive Design could become a significant factor in the process (Hemmingsson 2024, SwAM).

Hammar Perry (2024, GU) agrees and states that if Sweden were to have an auction-based system, it would have been possible to include enhanced positive biodiversity as a criterion. Although, Hammar Perry mentions that it would not be necessary since the reef effect gives rise to a positive impact on biodiversity even if nothing extra is done. He also states that there is a large will to include positive measures from the wind power developers, especially if there are low costs. Adding it as a criterion would be a good way to make sure the measures for enhanced positive biodiversity are carried out (Hammar Perry 2024, GU). Toivio and Stenegren (2024, CAB VG) express that it might be possible to incorporate biodiversity as a criterion in an auction-based system in general. In that case, implementing biodiversity measures would give companies an advantage and as a result companies would perhaps put more resources into increasing the knowledge around the reef effect (Toivio and Stenegren 2024, CAB VG).

8. Discussion

In this section, the contents of this master thesis are discussed. The discussion is related to the information gathered from the literature study, the case study and the interview study. The chosen topics are: Positive enhancement of biodiversity, wind power plants, importance of timing, importance of location, incentives to include NID, balance between climate change and biodiversity, and finally future research.

8.1 Positive enhancement of biodiversity

The complete definition of biodiversity has not been included in this master thesis. Biodiversity is a term that can have a wide variety of definitions, for example ecosystem, species and genetic diversity. The focus in this master thesis was mainly on species diversity, more specifically on individual species, their habitats and abundance, in a very local perspective. The larger area the wind power plants occupy and the more wind power plants that are built close to each other, the more relevant it would be to discuss ecosystem diversity. If all wind power plants that are planned on the Swedish west coast are built, the cumulative effects could potentially affect the ecosystem diversity.

Wind power plants and Nature Inclusive Design will enhance the habitats for local, hard surface associated, species. This is positive in our opinion since it will increase the variation and diversity of species in the area, probably improving the prerequisites for marine flora and fauna. There are a lot of different types of NID, but the most important aspect is to create a complex habitat. The more NID structures that are used in a wind farm, the more it will increase the hard surface area and create a more complex habitat. The more connectivity and the closer together the NID structures and the turbines are, the better.

It can be argued that NID might be unnecessary, since the foundations already contribute to hard substrate habitats. Although, they can further increase the complexity and surface of the habitats. It is also possible to design and optimize the NID units according to what the target species are. It is very important to consider which target species that you want to enhance the habitats for. A dialogue should be held with the CAB to make sure that the target species actually will benefit the ecosystem in the specific area. The local conditions are very important and differs between places. It is also a question about cost. For example, how many NID structures that can be afforded in a project and how many that are necessary to achieve the desired effect. The value of the biodiversity will indirectly be connected to the cost of the NID. Besides the increased reef effect from NID other positive side effects and their respective worth must also be considered. Examples of these positive side effects are the contribution to the spillover effect and a potential increased public acceptance. There are also huge possibilities with collaborations beside from NID including aquaculture, hydrogen production and oxygenation.

8.2 Wind power plants

A compilation of information about foundation types was presented previously in this master thesis. Jacket foundations were shown to be great from a fish perspective since they have more complex structures, while monopiles with scour protection are better for benthic fauna such as crab and lobster. Gravity foundations provide similar habitats and complexity as the monopile because of their scour protection. Besides the provision of habitat, the different foundations contribute to various magnitude of negative effects. It is hard to know what foundation is most suitable in each specific case, since it is very dependent on local geological conditions and depth. Usually, the conditions and the cost decides what foundations should be used in a project, but to also consider the reef effect qualities, such as complexity, would be beneficial.

The most negative effects occur during the first stage of a wind power plant's life cycle, the installation phase. During the operational phase, there are fewer negative effects and more positive effects. The decommissioning phase is more unclear, since it is not as well documented, but it depends on how it is carried out. If artificial reefs were to be built, it is important that they stay put even when the wind power plant is decommissioned, because of the established hard substrate community. This could be an aspect to consider when planning how NID structures are to be placed. If add-on cod hotels are used and mounted on the foundation, they will have to be removed regardless. Since they are designed primarily for cod, there are less hard surfaces compared to other NID structures. The removal would probably not affect the hard surface community as much since there is less fouling on a cod hotel compared to other NID structures. Although the cod hotels are usually mounted closer to the surface which means that they get more light, likely resulting in increased growth. If not only artificial reefs are left on the seabed, but foundations and scour protection as well, this could be beneficial for the hard substrate ecosystem community that have established there. Depending on how much is left on the seabed, meaning where the foundations are cut off, there will be various effects for the established species. An aspect to consider is that the foundations must be marked out very carefully if they are left on the seabed, protecting fishing equipment and preventing anchors getting stuck on them. There might be different opinions on if wind power plant foundations should be left on the seabed and it is important to have a discussion regarding this in the future when this matter becomes relevant.

With technical advancements, the capacity of the wind turbines increases as well as the size of the wind turbine and the distance between them. As presented in this master thesis, these larger wind turbines give rise to a potential change in the magnitude of the effects on biodiversity. The underwater noise is expected to be higher, the occupied seabed of one foundation will be larger, the sediments will spread to a larger area and the reef effect will probably be even larger as well, but with less connectivity in between turbines. Some effects, such as the reef effect, are harder to predict, while some are easier, for example the occupation of seabed. Another aspect to consider is that fewer but larger turbines might be needed for the same electricity production compared to the wind farms that exist today. This could indicate that the occupied seabed area might be smaller with larger turbines. At the same time the electricity demand is very large which means that more wind power will be necessary, causing the trend to steer towards larger wind power plants with higher electricity production. The interviewees stated that more research is needed on how these planned large wind power plants will affect the biodiversity, and how large the cumulative effects will be if multiple large wind power plants are built close to each other. Since the reefs around each turbine will be less connected to the other turbine reefs, NID could be a solution to increase the connectivity. Foundations and scour protection will increase in size when the turbine size increases which means they could function as independent reefs. Although, the reefs around the turbines will probably be of better quality if NID is used and as previously mentioned, they could contribute to increased connectivity if placed in between foundations.

Even if the planned wind power plants are large, they do not occupy a large percentage of the ocean. When speaking of enhancing biodiversity, it is very local and might have effects for the wind power plant area, but probably not on a large ecosystem or population level. When several wind power plants are discussed in a close proximity, there might be a case of actually affecting an ecosystem or population. The cumulative effects are hard to predict and can be both positive and negative. Focusing on the positive, several wind power plants with NID could make a larger difference in an ecosystem. Perhaps an area with soft seabed would change character towards a hard seabed ecosystem with associated species, completely different from before. Depending on the function of the ecosystem and potential risks with invasive species, this can contribute to stronger fish populations or similar effects. This might actually make a difference on a larger level. To get this effect, it is difficult to estimate how many NID structures are needed, and how large their influence is. It is also very important to consider the location. If there is an area with important values and unique environment, it is not suitable. Natural environments can be more complex than they appear, and all types of values contribute in a specific way. Therefore, it is important to consider all aspects. If a wind power plant is to be built, it will be a good idea to try enhancing the local biodiversity at the same time.

8.3 Importance of timing

Timing seems to be one of the major aspects determining the extent of the wind power plant's impact on biodiversity. If the installation is scheduled as to avoid the most sensitive time periods for fauna in the area, the negative impact is significantly reduced. This should therefore be done to the greatest extent possible. However, as previously mentioned this can be challenging for installation of offshore wind power. The installation depends on many factors such as wind and other weather conditions, and most likely also the availability of the installation vessels needed. To make the challenging process of installing the turbines easier it is presumably advantageous with calm conditions. In Sweden it is least windy during the summer season which unfortunately coincides with what is generally considered the most sensitive time period for the marine fauna. It is important that the installation of the turbines is done in a safe way, meaning a compromise might be needed. In that case it might be possible to adjust the scheduling to the most sensitive periods of select, valuable species present in the area. In case the installation must take place during the sensitive time period, the mitigation measures become very important instead.

Adjusting to the time period of the local fauna might also come with a downside. If the time window for conducting installation work during a summer season is shortened, it might necessitate an extension of the installation work for additional years. This would in turn lead to longer exposure to the negative effects. Lower but repeated exposure during several seasons might be worse than higher exposure during fewer seasons.

It is also important to consider the timing of installation for the NID structures, both for those placed on the seabed or scour protections and those used as add-on units. As mentioned in section 5.8.3, it is disadvantageous if the structures are covered with a layer of sediment as a result of the resuspended sediment settling. To avoid this, these structures should be put in place as a final step of the installation process. The importance of timing for the installation can also be discussed in the sense of becoming of use as quickly as possible. For example, it might be most beneficial to make sure the cod hotels, which are partly meant for juvenile cod, are put into place before the local spawning season so that it can be utilized once the cod reaches the right life stage. On the other hand, it might be more beneficial to put it in place earlier allowing more time to pass so that growth takes place, making the structure more natural to the fish.

8.4 Importance of location

Another important factor for making sure the impact on biodiversity is minimized is the choice of location. A good location can mean that a lot of unnecessary impact is avoided, and it influences what the effects on the chosen location will be. Location is of great importance since it determines factors such as depth, salinity and temperature of the water, the type of seabed, and mixing of the water. All this combined affects what species are present in the area and thereby how large the impact will be, both negative and positive. This in turn determines what measures should be used to mitigate negative effects and measures available to enhance the positive effects. How effective the NID will be is also influenced by the location.

This complicated relationship can be exemplified with the site-specific factor of depth. Firstly, the depth influences the choice of foundation, which directly correlates to the magnitude of the effects. Secondly, it influences what species will be present at the location and therefore can be affected. What species are present depending on depth is related to if the light can reach the seabed or not. If light does not reach the seabed, which is the case for many wind farms planned today, there is less variety and less valuable species at the bottom. From the perspective of occupying the seabed this is advantageous. However, this might also mean there are fever species that will benefit from NID and therefore it once again becomes important to know what species to focus on in a specific project. Another example of this relationship was encountered in the case study of West Wind. The seabed conditions will not only influence the choice of foundation as well as what species are present at the location, it also constitutes a limiting factor for the use of NID. The risk of compromised structural integrity caused by poor bearing capacity of the soft seabed restricted the possible placement of NID structures, which might cause them to be less effective.

With this in mind, it is important to understand the site in order to limit the negative effects and to implement the best solutions using NID. Some locations might be better suited for using NID than others. Perhaps NID are better used in shallow waters than at depth of modern wind power plants. On the other hand, if the characteristics of a location are to be changed by the installation of a wind power plant, an attempt to optimize the new habitat should be made. Since the location influences the outcome to such a vast degree, relying solely on research done in other countries will not suffice. Projects must be initiated in Sweden to obtain results valid for Nordic conditions. It is also particularly important to cooperate with the countries sharing waters with Sweden, such as those in the Nordic or Baltic Sea region.

8.5 Incentives to include NID

In today's permitting system, the focus is to assess if a wind farm is admissible and that negative impacts are mitigated as far as possible. Positive enhancement of biodiversity might be considered but is not the focal point, especially since there are different opinions on what positive enhancement of biodiversity actually means and that the ecosystems are complex. Positive enhancement of this kind should, according to us, not be classified as compensation, since this is associated with restoring negative impact. It should instead be classified as positive biodiversity. It could potentially be classified as net gain or net positive impact on biodiversity. Perhaps removing soft seabed and replacing with hard substrate could be considered as net positive impact, since it is of a different character than the original value.

We are hopeful that enhancing biodiversity will play a larger part in the future, since there seem to be a unified view of the importance. If a change to a system where the government designates suitable areas for wind power, positive enhancement of biodiversity could be a criterion. This would create the possibility of giving an advantage to using NID. We believe that this would be beneficial for increasing the usage of NID and including biodiversity even more. Although, it might be a challenge to change the permitting system in Sweden short term because of the many applications currently under assessment. Our opinion is that it is better to use resources to improve the current system and find an alternative incentive to include NID.

Cost plays a large role in wind power projects. If companies get some sort of advantage by using NID, the probability of them including NID in their projects increases. There is another point of view that NID could possibly contribute to the general public's acceptance of wind power. Increased acceptance has not been established but is a concept which would be interesting to explore. If companies were to promote their engagement in enhancing the local marine biodiversity, the public acceptance might increase. Public acceptance could indirectly become an advantage in the permitting process, in case endorsement from municipalities is needed. It can also be a opportunity to emphasize that NID could promote the spillover effect, which can be used as an argument to create acceptance from the fishing industry. Companies developing wind power plants have a unique role to be able to implement NID and similar measures and contribute to knowledge and science. By collaborating with organisations and universities, there would be an opportunity to test and monitor NID on a large scale, in real applications, over a long period of time. By sharing knowledge and ideas between each other, companies can fill in knowledge gaps together and collaborate towards a better understanding of the reef effect, the effects of larger wind power plants and the effects of NID.

Based on all the information gathered, it is believed that at least some wind farms should be closed off for fishing, for the sake of biodiversity. Overall, it appears to be very beneficial for the species affected by fishing and their ability to recover. However, this may not be feasible for every location. If the installation and especially the decommissioning is done extra carefully, offshore wind farms should be able to function as protected areas. If they meet any potential requirements to be classified as a protected area, this could contribute to meeting EU's target to protect 30 percent of marine areas. If a wind farm is protected from fishing and similar activities, this will ensure higher survival of fish stocks and an increased potential of the spillover effect. However, if coexistence with fishery is important to get a permit, we believe that renewable energy is more crucial than extensive protected zones. If that is the case, a smaller protected area can be implemented inside the wind farm, where the NID structures are placed. The focus in the rest of the wind farm could then be to optimize the scour protections. A similar solution to this was proposed in the case study for West Wind.

8.6 Balance between climate change and biodiversity

As previously mentioned, the issues with climate change and reclining biodiversity are connected. Climate change is one of the largest drivers of biodiversity loss and a functioning ecosystem is a crucial part of a stable climate. It is possible to combine fossil free energy production and nature conservation. Wind power plants give rise to some negative effects on biodiversity, but with planning and protective measures, these effects are possible to minimise. There are solutions to enhance the local biodiversity in combination with offshore wind power plants, such as NID. In order to find the balance between climate change and biodiversity in the aspect of wind power, the way forward is to build wind power plants and carefully monitor the effects and take necessary precautions thereafter, in future projects. How large the potential cumulative effects are from many large wind power plants is hard to establish without building. Of course, there must be continuous communication within and between countries to have a sustainable development. Even if a lot of offshore wind power plants in an area can change the ecosystem from soft seabed to more hard seabed which can be seen as a negative thing, it can also increase the species diversity.

8.7 Future research

From this study, more knowledge gaps that were previously unknown to us have been discovered. Since one idea is to have positive biodiversity as a criterion in an auction-based system, it is important to find out the best way of doing this, to ensure the right objectives are promoted. There is a possibility that an advantage can be given to those that include NID in their project plans and another that it should be a requirement in order to be included in the auction at all. It is difficult to know the most suitable way to implement this system since the local conditions play a large role, and different ways can be optimal in different areas. Another aspect that can be studied further is how marine spatial planning can be done in a better way, to prevent cumulative effects and competing interests.

To be able to classify the reef effect and NID as positive for certain species and in that way enable it to become an advantage in the permitting process, more research is required. The effects of NID need to be studied, primarily in Nordic waters and at depths with limited sunlight. It is important to perform practical field studies to find out the optimal number of structures needed to increase the reef effect as efficiently as possible. Researching the optimal placement of NID structures to get connectivity within the wind power plant is also important. The long-term reef effects should be studied in order to better understand the development. If the spillover effect is possible to verify for fish, it could lead to opportunities to achieve better coexistence between fishing and wind power. New fishing methods adapted for use in wind farms should be developed to further increase the coexistence. This can be useful in cases where fishing decreases the feasibility of a wind farm in an otherwise promising location.

Effects on biodiversity from large wind power plants have been discussed in this master thesis but the true effects can only be established if wind farms are built and monitored. Since for example cables were excluded from the scope, it could be interesting to investigate how they can be utilized in combination with NID to increase the connectivity in a wind farm. Biodiversity is not only affected locally where the wind farm is built, but also in the value chain when the materials are sourced and transported. This should further be investigated in order to ensure minimal negative impact. In order to measure the effects on biodiversity, either negative or positive, a science-based approach should be adapted. Targets that are reachable and measurable should be set by companies developing wind power plants. Since there are different opinions concerning the valuation of biodiversity, it is important to establish a unified method to value biodiversity, including economic value. However, determining the value of biodiversity is a very complex issue. Additionally, a framework should be established that includes what measures should be implemented depending on the objectives and the effects, to enhance habitats for certain species.

9. Conclusions

In this master thesis, the studied effects on marine biodiversity were underwater noise, sediment spreading, seabed occupation and the introduction of hard substrates. The magnitude of the effects depends on local conditions, installation and design choices. When using protective measures presented in section 5.7, the negative effects are possible to minimise.

To conclude this master thesis, the main finding is that Nature Inclusive Design has a great potential to enhance local biodiversity if implemented in the right way. The interest in these kinds of measures is large, and we are hopeful that it will be included in more wind power projects in the future. More research is necessary to establish the long-term effects on how biodiversity is enhanced by Nature Inclusive Design. If this is established it could ensure that positive enhancement of biodiversity can be used to potentially get an advantage in the permitting process in the future. Research is also needed to establish the effects from large wind power plants on biodiversity as well as the cumulative effects from many wind farms as these effects are still relatively unknown. The only way to proceed in the research is to build wind farms and conduct meticulous control programs. In our opinion, wind power developing companies have a responsibility to participate in the research and collaborate with other actors in the industry to gain improved knowledge in these matters. It is also important to take advantage of the possibilities of coexistence between different interests inside a wind farm area. This can contribute to advantages for several parties and make the projects feasible from a permitting perspective. Early inclusion of representatives from different interests is key to ensure a favourable collaboration.

From information gathered during interviews, it was identified that Nature Inclusive Design and enhancement of biodiversity are concepts of increased interest in offshore wind farms. The reef effect is confirmed in the scientific literature, but opinions on whether it is positive or not differs depending on the nature conservation objectives in the area. It is important to consider what the target species for the design choices are, and to include this early in the planning stage. The wind farms give rise to the reef effect regardless, but optimized design choices and Nature Inclusive Design can further enhance the reef effect and promote habitats for different hard substrate associated species. The most important aspects that are beneficial for hard substrate associated marine fauna are complex hard surface habitats with cavities of varying sizes.

If the long-term positive effects are established, Nature Inclusive Design can be considered as a potential benefit for a wind power plant permit application in today's system. However, it cannot compensate for considerable negative impact and therefore make the wind farm admissible. If there would be an auction-based system in Sweden in the future, enhancing positive biodiversity can become a criterion and therefore give an incentive to include Nature Inclusive Design.

Considering the important relationship between climate change and biodiversity, where each influences the other, it is crucial to establish a balance between them. In this balance, offshore wind power plants are being built without negatively impacting biodiversity, and maybe even enhancing the marine subsurface biodiversity. With these proposed mitigation strategies, design choices, and Nature Inclusive Design, the marine subsurface biodiversity could be enhanced and benefit from wind power plants, and a balance can be established.

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A. Interview questions

A.1 Intervjufrågor till Länsstyrelser:

- Vad är er roll i tillståndsprocessen för havsbaserade vindkraftsparker i territorialvattnet och ekonomisk zon?
- Hur behandlas och värderas biologisk mångfald i tillståndsprocessen?
  - Finns det ett system för att kvantifiera eller värdera påverkan?
  - Hur stor kunskap finns kring biologisk mångfald generellt hos er på Länsstyrelsen? Har ni stor kompetens kring biologisk mångfald kopplat till havsbaserad vind?
  - Vilken miljöeffekt väger tyngst? (Klimat, biologisk mångfald, kulturmiljö, socialt etc. . .)
  - Hur platsspecifikt är olika värderingar av påverkan på djur och växtliv?
  - Har olika typer av arter olika värde, beror det på platsspecifika förhållanden?
- Finns det en fördel i tillståndsprocessen med att ha förhöjd positiv påverkan på biologisk mångfald? Kommer det beaktas om det finns en förhöjd positiv påverkan på biologisk mångfald?
- Kan förhöjd positiv påverkan på biologisk mångfald liknas vid kompensation för negativ miljöpåverkan? Går förhöjd positiv påverkan att placera in i skadelindringshierarkin?
- Hur ser det ut i framtiden för att inkludera biologisk mångfald mer i tillståndsprocessen, är det på gång?
- Ser ni några förändringar i hur tungt den biologiska mångfalden väger i tillståndsprocessen? Är det på väg att bli viktigare och viktigare?
- Hur tycker ni att tillståndsprocessen kan effektiviseras, är biologisk mångfald/värdering ett hinder? Finns det risker med att effektivisera tillståndsprocessen?
- Vet ni om det finns planer/funderingar på att införa auktionsbaserade system, för att undvika konkurrens mellan aktörer för samma projekteringsområde? Kan positiv påverkan på biologisk mångfald bidra till extra fördel i så fall?
- Finns det några idéer, styrmedel eller initiativ som kan vara relevanta för att främja biodiversitet i framtiden?