

Decommissioning of offshore wind farms

The nature based business case of scour protection



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This report is an initiative of The Rich North Sea program and executed by professionals of ECHT-Regie in Transitie.

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Preface

The Rich North Sea seizes the unique opportunity offered by offshore wind farms to enhance nature in the North Sea. Due to the various practical projects the program entails, The Rich North Sea is gaining extensive knowledge and insight into nature enhancement in wind farms.

The program also investigates whether natural values that have been created or arisen in offshore wind farms can and should remain in place at the end of the offshore wind permit. To answer these questions, research is conducted via three pillars: 1) The legal regarding the duty to decommission within the international, European, and national legal framework. 2) Nature's value through the KOBINE project, by quantifying the natural gains with a focus on water quality, biodiversity, and biomass. 3) The financial costs of removing and benefits of leaving parts of the wind farm in place to conserve the natural values. The results of these three pillars together provide an overall picture of the legal possibilities and accompanying financial and natural impact.

This research focuses on the third pillar. By investigating the costs and benefits of leaving scour protection behind. First, the current situation is described using the latest literature and applicable laws. Thereafter, the decommissioning alternatives are described including the decision to focus on scour protection. At last, both monetized and ecological costs are assessed and substantiated.

For this research, several experts from the industry were consulted. These experts are not mentioned because it could create unwanted insights in their internal cost calculations. On top of that, the researchers made assumptions about certain factors like the density, volumes, decommissioning process, costs, etc. These values can differ per location of the windfarm, type of turbine, decommissioner, permit requirements, etc. Therefore, the reader is urged to take this calculation solely as a first insight in the financial impact of scour protection decommissioning.

The idea of this research is to open the discussion about removing scour protection and the relationship between economic and ecological effects.

This research focusses on the Dutch part of the North Sea.

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List of acronyms

BS	Below seabed alternatives
CR	Complete removal alternative
DRA	Designated reefing area
MPA	Marine protected area
O&G	Oil and gas
OWF	Offshore wind farm
WTG	Wind turbine generator
ROV	Remote Operating Vehicle
NWEA	Nederlandse Wind Energie Associatie
MW	Megawatt
GW	Gigawatt
MP	Monopile
RVO	Rijksdienst Voor Ondernemend Nederland/ Netherlands Enterprise Agency

1

Introduction



1. Introduction

1.1 Background

In the recent Climate Agreement, the Dutch government set the goal of a carbon-neutral energy supply by 2050 (Rijksoverheid, 2019). To achieve this ambitious target, offshore wind energy has become a main pillar of climate policy (Rijksoverheid, n.d.). Between 2030 - 2050, the installed capacity will be between 38GW and 72GW, which corresponds to 7.5% and 13.4% of surface occupation in the Dutch part of the North Sea (Rijksoverheid-b, n.d.).

Simultaneously, the Dutch North Sea is subject to environmental objectives regarding nature recovery and conservation (Fowler, et al., 2020). The recent North Sea Agreement acknowledges that biodiversity is declining, and soils are disturbed (Rijksoverheid, 2020). Yet, as argued in the North Sea Agreement, “objects and installations that create new habitats can contribute to nature restoration” as they provide hard substrate in a dominantly soft-sediment environment (Rijksoverheid, 2020; Birchenough & Degraer, 2020). Marine species use such new habitat to settle, spawn, forage and refuge, thereby increasing local biodiversity and biomass, so-called ‘artificial reef effects’ (Birchenough & Degraer, 2020; Coolen, et al., 2020; Fowler A. M., et al., 2018; Teunis, et al., 2021)

Offshore wind structures also have been found to induce artificial reef effects (Degraer, et al., 2020). Additionally, OWFs are prohibited from trawl-fisheries and heavy vessels, consequently protecting the area from bottom-disturbing activities. Thereby the opportunity for environmental flourishing is strengthened (Van Duren, et al., 2016; Ounanian, van Tatenhove, & Ramírez-Monsalve, 2020). Consequently, OWFs could represent an effective overlap between nature and energy targets at sea. It is however unlikely that these thriving habitats will exist indefinitely because at some point OWFs will have to be decommissioned, i.e., dismantled and removed (Fowler A. M., et al., 2018). The first Dutch OWFs to be decommissioned will be the Egmond Aan Zee and Prinses Amalia wind farms, in 2026 and 2027 respectively (Teunis, et al., 2021). An offshore wind turbine lasts for approximately 20-30 years before being no longer profitable due to failure or fatigue (Smyth, et al., 2014). Moreover, permits granted for offshore wind sites are only valid for 30 years in the Netherlands and include an obligation to remove all structures at the end of this period (Teunis, et al., 2021).

Considering the ecological benefits these offshore structures can provide, scientific consensus is reached to review current decommissioning laws and regulations (Fowler, et al., 2020). Complete removal will not only eliminate the reef effects but also reopen the area to bottom-disturbing trawl fisheries (Adedipe & Shafiee, 2021; Fowler A. M., et al., 2018; Fowler, et al., 2020; Kerkvliet & Polatidis, 2016; Smyth, et al., 2014). In contrast, retaining portions of the foundations can significantly reduce decommissioning impacts. As a potential outcome, the area may qualify for designation as a protected area if it has established natural values, thereby safeguarding the existing ecosystem from additional seabed disturbance and potentially contributing to conservation targets e, (Ounanian, van Tatenhove, & Ramírez-Monsalve, 2020; Topham, Gonzalez, McMillan, & João, 2019).

The “legal framework” research by Utrecht University from the other pillar shows that international law allows the coastal state to decide to leave an artificial reef intact and to justify it legally. It is important that a legal distinction is made between two types of objects to which partly different rules apply:

artificial reefs placed between wind turbines, and objects installed on or forming part of the foundation of scour protection of wind turbines. For both categories of objects, both international and European law apply that there is no unconditional obligation to clean up. In principle, the coastal state has the freedom to decide at its own discretion about cleaning up artificial reefs or leaving them intact within the relevant assessment frameworks set by international and European law (Holst, 2022).

Nevertheless, decommissioning decisions are politically sensitive due to the involvement of many stakeholders who are accompanied by differing interests. Decommissioning may affect other North Sea users such as shipping, fisheries, military, oil and gas, sand extraction and nature. Users of the North Sea may hold diverse perspectives and interests concerning the decommissioning methodology and the necessary jurisdictional framework. Incorporating their opinions into the decision-making process may result in outcomes that differ from the currently mandated methodology (Jurrius, 2021). Ultimately, the decommissioning playing field involves a widely varying stakeholder group, where the political climate has underlying influence yet is also driven by industry and society.

Apart from this, the offshore decommissioning industry is essentially also still in its infancy. To date, decommissioning of offshore wind turbines has only been performed on a small scale compared to future operations, both in the number and size of turbines (Table 1). The large-scale removal of OWF in the coming decades is challenged by large volumes and a lack of experience (Smartport, 2020). Therefore, it is a challenge to understand the financial and ecological cost of decommissioning.

Turbines/wind farms	Country	Number, turbine size	Foundation	Built	End of service	Removed
Nogersund/ Blekinge/Svante	Sweden	1x220kW	Tripod	1991	2004	2007
Yttre Stengrund	Sweden	5x2 MW	Drilled MPs	2001	2015	2015
Robin Rigg (2 of 60)	UK	2x3 MW	MP	2010		2015
WindFloat	Portugal	1x2 MW	Floating	2011	2016	2016
Hooksiel	Germany	1x5 MW	Tripile	2008	2011	2016
Lely	Netherlands	4x500 kW	MP	1994	2014	2016
Vindeby	Denmark	11x450 kW	GBS	1991	2016	2017

Table 1: Decommissioned offshore windfarms (Smartport, 2020)

To conclude, offshore wind capacity in the North Sea is set to expand significantly over the next decades. The Dutch North Sea is subject to environmental change, but wind turbine foundations can potentially contribute to nature enhancement. Despite the ecological benefits such structures can provide, permits obligate them to remove all offshore structures at the end of their lifetime. The different interests of stakeholders and limited experience with decommissioning make it currently difficult to decide if leaving a certain part of the structure in place is the right thing to do. Though, international law allows the coastal state to decide to leave an artificial reef intact and justify it legally. It should be emphasized that this legal condition must never be used solely as permission to leave something behind in the sea without consideration of other value creations.

1.2 Problem definition

The current legal framework states that all offshore wind infrastructure must be removed and cut off up to 6 meters below the seafloor at the end of its lifetime which is not decided upon specifically yet (Teunis, et al., 2021). Decommissioning offshore infrastructure costs substantial money. Based on, among other things, the amount of offshore lifting and operating time (Topham, Gonzalez, McMillan, & João, 2019). Decommissioning also causes disturbance to natural values, whereas leaving part of the foundation can potentially be beneficial for nature. Moreover, it would be contradictory to remove the natural values established during the lifetime of the wind farm, only to replace the site with a new wind farm (repowering) in the future, which may include artificial reefs to support nature development, like what has been done at the Hollandse Kust West site VI. Leaving part of the foundation behind minimizes disturbance, which is beneficial for the local ecosystem, and could save offshore wind farm operators money that could be used for more nature investments. The question is whether there is a business case for leaving infrastructure behind so that wind farm owners can invest more in nature.

1.3 Research questions

What would be the financial and environmental costs and benefits of leaving part of the offshore WTG foundation behind?

- Sub question 1: What are the environmental and financial considerations of different decommissioning strategies?
- Sub question 2: What are the differences in cost between leaving scour protection behind compared to complete decommissioning?
- Sub question 3: Could offshore wind farm developers invest more in nature with the saved expenses compared to complete decommissioning?

1.4 Scope

For this research, boundaries are set, as this research will function as a general cost estimation based on key figures and knowledge from the actual industry practice. Each wind farm has specific data (location, date, turbine, scour protection). This data is known for Dutch offshore windfarms, therefore, the scope is set to the Dutch offshore wind farms. Those windfarms typically have a water depth of 15–35 meters, are located 15–40 miles offshore and have a traditional monopile foundation with a rock-based scour protection consisting of a filter and armour layer. Additionally, it is important to note that the research does not delve into the details of transportation of stones to a certain location and reusing the stones.

2

Current situation



2. Current situation

Offshore wind farms are still relatively new, and therefore operators/owners have been mainly concerned with improving installation techniques and accomplishing operational efficiency. Despite the potentially extensive costs, logistical difficulties and environmental impacts, decommissioning has been given little thought to date. This is an important topic because decommissioning is a significant part of any project, and should be considered from the very beginning, from the design stage, as if not done then, impacts can become more serious, and costs can be higher than expected (Topham & McMillan, 2017).

Upon searching online, the term 'decommissioning' is commonly found on the websites of involved stakeholders. Given the prevalence of the term 'decommissioning' on these websites, it can be inferred that this topic is of significant interest to companies, associations, and governments.

NWEA the Dutch Industry association of the wind sector for example posted an article on their website about decommissioning and circularity (NWEA, 2021). TKI Wind op zee who stimulates the development of offshore innovations through research and development and published a "lifecycle and decommissioning offshore wind" report in 2016. This report mainly focuses on different end-of-life options for offshore wind farms (Bulder & Van Roermund, 2016). RVO, the Netherlands Enterprise Agency published a development report for offshore wind in 2021. This report assumes that wind farms will be decommissioned and say that it is conceivable that the designated offshore wind energy areas will remain designated as wind energy areas after the life cycle of the first wind farms and that new wind farms can be developed in those areas (Ministerie van Economische Zaken en Klimaat, 2021). WindEurope also pays attention to the topic in their Wind-energy-in-Europe 2021 statistics report. This report mainly discusses whether offshore wind farms will be decommissioned or repowered after their lifetime (Wind Europe, 2022).

While it is clear that decommissioning is receiving increasing attention, it is noteworthy that most articles focus on the technical challenges associated with offshore wind decommissioning. However, there seems to be a lack of emphasis on the ecological impact of decommissioning and the promotion of nature-friendly alternatives, which do not appear to be high on the priority list at present. Besides, costs of the decommissioning process are hardly mentioned.

2.1 Current decommissioning policy

The "legal framework" research by Utrecht University from the other pillar explains that one of the obligations arising from the Law of the Sea Convention is the general clearing-up obligation for 'installations and establishments' in Article 60 paragraph 3. This means that currently, the complete offshore wind foundations must be removed (Holst, 2022).

2.2 Number of offshore wind MW to be decommissioned

In the coming decades, there is expected to be a significant increase in decommissioning activities in the North Sea (Teunis, et al., 2021). In the southern North Sea, the amount of annual capacity to be removed will increase from 20 MW to a maximum of 3700 MW between 2020 and 2050. The wind turbine foundations will need to be decommissioned after their operational life of 20–30 years. The development of the installed power will largely determine the number of wind turbines to be removed per year, as shown in Figure 1 (Smartport, 2020).

Most urgent cases in the Netherlands are OWF Noordzeewind (Egmond aan Zee) and Prinses Amalia that will reach their end of life in 2026 and 2027. Because preparations for such operations will take several years, it is important for the offshore wind farm operators to start the discussion with stakeholders and the Dutch government about the decommissioning plans.

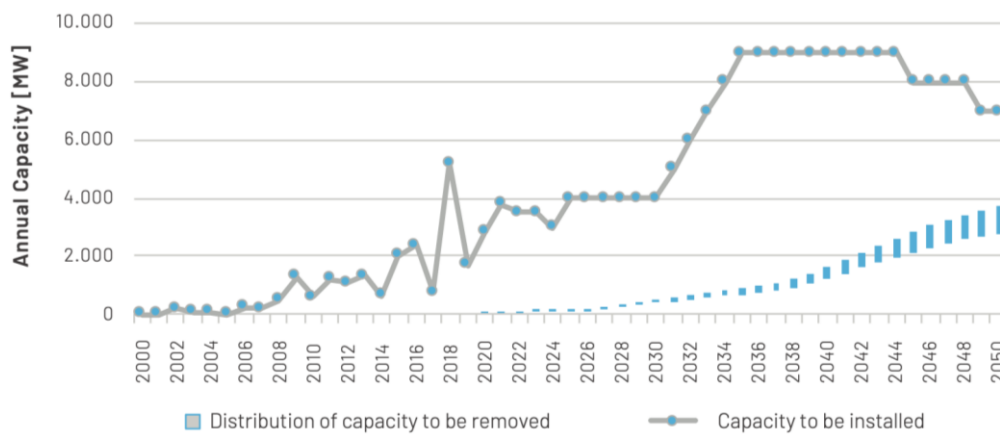


Figure 1: Projection of annual offshore wind capacity to be installed and removed in the North Sea [MW] (distribution is based on lifetime variation from 20–25 years to 25–30 years) (Smartport, 2020)

2.3 Common foundation types

Various foundation types are used in the offshore wind industry, but in the Netherlands only monopiles are used because of their suitability for relatively shallow depths of 10–30 meters (Gjørdvad & Ibsen, 2016), small marine footprint compared to other bottom-fixed foundation structures (Kapsali & Kaldellis, 2012) and show low manufacturing, transport and installation costs. Monopiles are steel piles that are driven into the seabed to a depth of over 22 meters (Kapsali & Kaldellis, 2012).

Because ocean currents erode the sediment around the monopiles, a protection layer consisting of loose rocks, called scour protection, is installed on the seabed around the base of the monopile to counter the erosion process (Teunis, et al., 2021). Scour protection usually covers 4–6 times the monopile diameter (Lengkeek, et al., 2017).

2.4 Decommissioning effects on ecology

The impacts of decommissioning activities on marine habitat types and species can be separated into effects during decommissioning and effects after decommissioning.

Decommissioning activities cause a variety of risks that can potentially cause an ecological impact on present marine ecosystems. The actual ecological impacts of decommissioning depend largely on the type of foundation present, the decommissioning strategy chosen and the duration of the activity (Teunis, et al., 2021). Decommissioning activities cause noise pollution and vibrations, bottom disturbance, and turbidity. Moreover, risks arise of chemical pollution during removal activities and the possible spread of non-native species during transportation to shore. All the above aspects can potentially cause an ecological impact on present marine ecosystems (Teunis, et al., 2021).

Current ecological impact assessments commonly assume that expected disturbances during decommissioning of the turbine and foundation structure, like noise- and vibration levels, do not exceed levels experienced during the construction of the wind farm, and are of a temporary and local nature. Therefore, ecological impacts caused by noise- and vibration levels during decommissioning are considered to have the same (or less) impact as during the construction of the wind farm. Mitigation measures like the ones applied during construction processes can also be applied here to minimize the impact.

After decommissioning, several aspects of a wind farm that have an ecological function may (partially) be removed. Such aspects are the artificial hard substrate, exclusion zone of bottom disturbing fisheries and disturbance in stratification layers. The most important environmental impacts are described below:

Advantageous of decommissioning:

- The artificial hard substrate not only attracts native epifauna species but can function as a steppingstone for non-native epifauna species. Non-native species mainly reside in the intertidal zone of the monopile. Complete removal of the wind farm and its artificial hard substrate also removes the steppingstone function of the wind farm site for non-native species (Teunis, et al., 2021).
- The complete removal, and probably also partial removal, of an offshore wind farm reduces the risk an offshore wind farm poses to the ocean's stratification layers. Namely, large-scale offshore wind farm developments can disturb the stratification layers, and thus can affect biological activity (phytoplankton production). Removal of monopiles directly removes the risk of disturbance in the stratification layers on site (Teunis, et al., 2021).

Disadvantageous of decommissioning:

- After decommissioning the hard substrate (scour protection, monopile and other types of foundation) is no longer present or remains only partially present. As a result, the epifauna community, which has colonized the substrate in its 20–25-year life span, is also (partially) removed. Moreover, the function of the artificial hard substrate as a foraging, hiding or spawning habitat for associated species like certain fish and mobile macrobenthos will be removed (Teunis, et al., 2021).
- Besides acting as a steppingstone for non-native species, the artificial hard substrate can also act as a steppingstone for valuable or protected native species, for example, flat oysters *Ostrea edulis* (Teunis, et al., 2021).
- The eventual exclusion of bottom trawling fisheries in offshore wind farms leaves the sea floor undisturbed for the lifespan of the wind farm, potentially favouring the development of long-lived species or even biogenic reef systems. The removal of the wind farm can harm these valuable or protected species or reef systems, as hard substrate is removed. And without qualification for designation as a protected area bottom trawling fishery are allowed to return on site (Teunis, et al., 2021).

3

Alternative decommissioning strategies



3. Alternative decommissioning strategies

Reusing the foundation structures by replacing the old turbine with an improved turbine, i.e., repowering, is an often-mentioned strategy (Topham & McMillan, 2017). However, its potential for OWFs that will reach their end-of-life phase in the Netherlands in the near future is minimal. Their foundations do not offer sufficient support as modern turbines have grown rapidly in size (TNO, 2020). This was confirmed in interviews, in which the size and lifespan of the foundations and the shallow sea depth, in addition to high spatial pressure, are mentioned as practical problems of repowering the earliest OWFs. Hence, repowering of foundations was not further examined (Jurrius, 2021).

Several studies have aimed for a holistic comparison between offshore foundation decommissioning strategies, these often compare them on 'high level' differences: full decommissioning versus partial decommissioning (Adedipe & Shafiee, 2021; Gjørdvad & Ibsen, 2016; Smyth, et al., 2014; Topham & McMillan, 2017). Jurrius (2021) considered sub-options as well, together with the possibility of establishing a marine protected area (MPA). These strategies, as shown in Figure 2, are elaborated on further in appendix I.

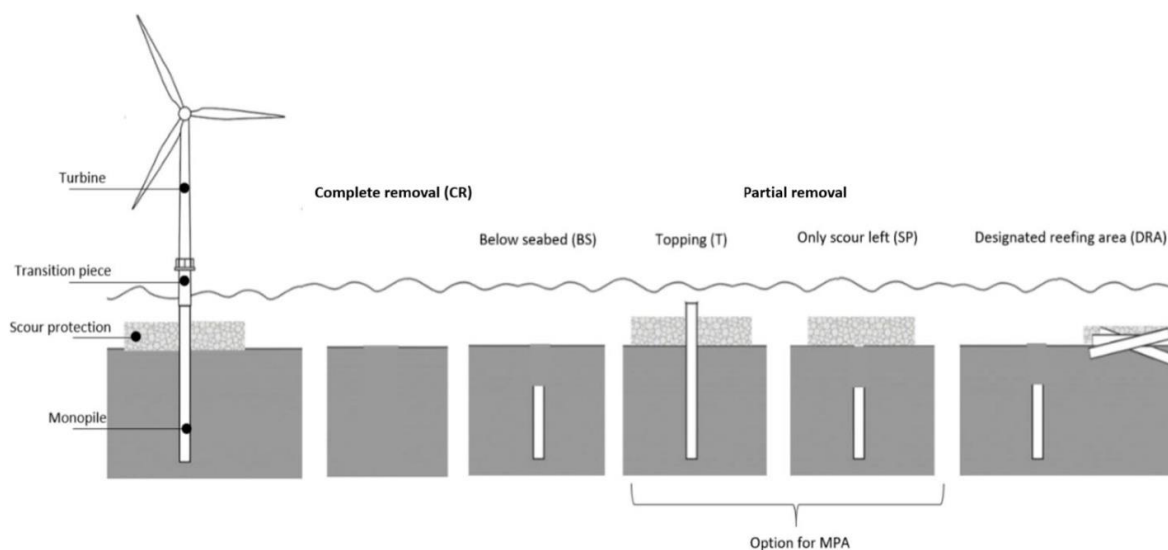


Figure 2: An overview of offshore wind turbine installation and the decommissioning strategies examined by Jurrius (2021)

The unique characteristics and historical ecological values of each site require a more adaptable strategy for decommissioning. Such a strategy must balance the complex trade-offs involved, such as environmental impact and economic costs. It's crucial that the industry does not compromise the benefits to the environment in the pursuit of fulfilling its responsibility to clean up. Rather, a solution must be found that balances both concerns. This requires a decommissioning process that prioritizes environmental impact over financial or emotional considerations. Given the diverse array of offshore structures and the species that inhabit them, there is no one-size-fits-all solution. Each decommissioning effort must be tailored to the specific location and species involved. For instance, unique protected species, repowering, marine spatial planning, biomass, and more could influence a unique strategy which could fit better to the local environmental impact.

Considering the above and the in appendix I discussed decommissioning alternatives it is important to choose one decommissioning alternative to calculate the financial cost and benefits. The “only scour left” alternative appears generally to be the most beneficial for nature. Scour protection contains the highest ecological values, besides that, this alternative is more accessible compared to the other alternatives because only the monopile is removed whereas scour (a natural substrate) is left behind. Moreover, there are fewer risks as the duration of the decommissioning activities at sea is shorter and less fierce (Jurrius, 2021). This also leads to decreased temporary disturbance of the marine environment. Finally, leaving scour behind also means that bottom-disturbing activities such as bottom trawling fisheries cannot return. The “only scour left” option leaves the discussion open to remove the complete monopile or to cut it six meters below the seafloor. This discussion is out of scope for this research. However, during that discussion, the involved stakeholders should consider that the “only scour left” option aims to leave the epifauna on the scour protection undisturbed.

4

Scour protection



4. Scour protection

In literature, scholars often refer to scour protection as “stones around the wind turbine”. While this is true, a more in-depth understanding of the protection is needed before the costs of the removal of scour protection can be calculated.

Scour protection is a crucial element in the design and construction of offshore wind farms. It involves the installation of a multi-layered system that can withstand the effects of wave, current, and tidal action. The first layer, called the underlayer, is usually composed of sand or gravel and provides a stable foundation for the scour protection system (the seabed). The second layer is the filter layer, which acts as a barrier against soil erosion and sediment transport. It is typically made of a graded stone, and its thickness and permeability are carefully designed to ensure that it can withstand the hydraulic forces induced by the waves and currents (rock manual, chapter 3). The third and top layer is the armour layer, which is composed of larger rocks that protect the underlying layers from erosion and scour. The armour layer is designed to dissipate the wave energy and prevent the filter layer from being displaced or washed out. To enhance the scour protection system's effectiveness, an additional filter layer can be added between the underlayer and the filter layer. This layer further filters the water and prevents fine particles from entering the filter layer, thereby increasing its lifespan. The design of scour protection systems must consider the specific site conditions, such as the seabed topography, the water depth, the wave and current climate, and the sediment characteristics (rock manual, chapter 5). The choice of materials and construction methods must also comply with industry standards and regulations to ensure the long-term sustainability of the wind farm. Figure 3 shows an example of a typical scour protection system used in offshore wind farms.

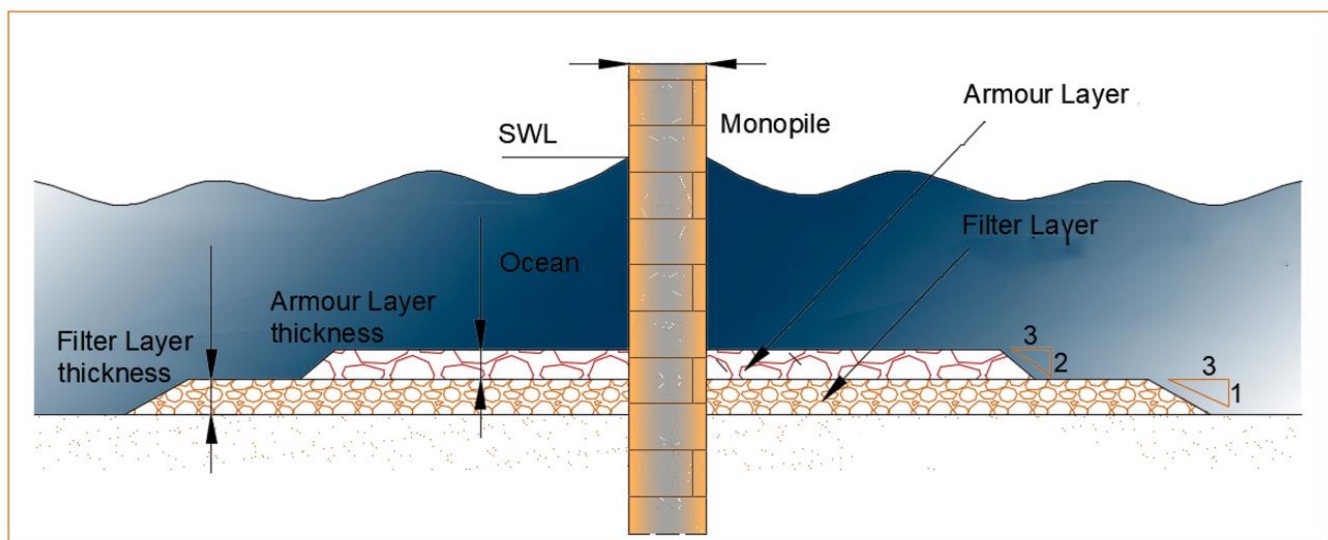


Figure 3 : Scour protection monopile (Dolores Esteban, López-Gutiérrez, Negro, & Sanz, 2019)

4.1 Scour protection in practice

Nowadays, most scour protection is placed with a fall pipe vessel. During construction, the contractor monitors the amount of ton's placed per m². During and after the construction the vessel positioning systems and depth surveys allows them to install rock armour with high accuracy. After the operation, the contractor must prove that the rock armour is placed within set boundaries, this is often done with multibeam survey (Figure 4 & 5).

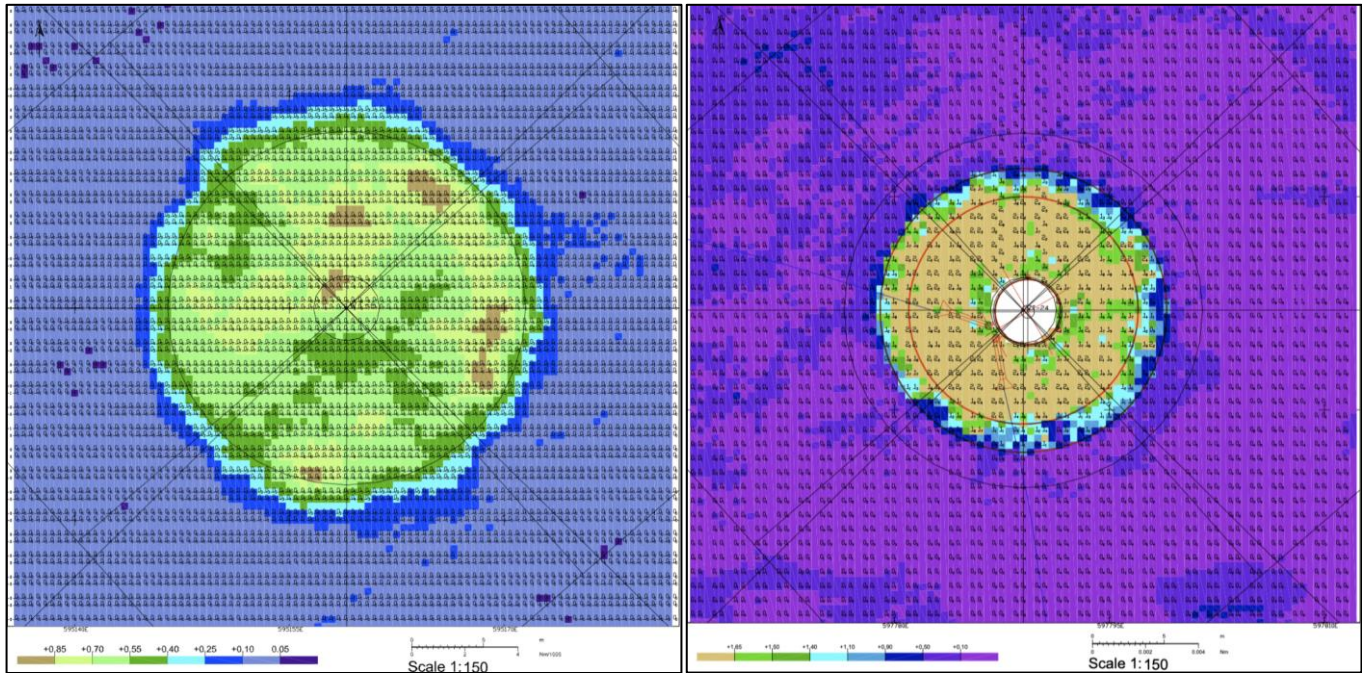


Figure 4 & 5: As-built scour protection multibeam (anonymous offshore wind farm).

It is clearly visible that the diameter of the filter layer is bigger than the armour layer (as per design principle). Also, it can be seen that the contractor placed stones outside the design diameter (black circle line) to be sure that they fulfil the employer requirements.

The height of scour protection is not evenly levelled, this is indicated by the different colours in figure 4&5. The dark green colour represents the design values. Blue dots represent that the area is under the minimum criteria while light-green, yellow, and brown are above the design level. It can be concluded that in practice the contractor installs significant more rock armour than theoretically calculated, to have more certainty about reaching the minimum requirements set by the developer.

4.2 Common dimensions

For some wind farms the current dimensions are publicly known. For instance, (Esteban, López-Gutiérrez, Negro, & Sanz, 2019) discussed the scour protection characteristics of 5 case studies including Dutch offshore wind farms Princess Amalia and Egmond aan Zee (Figure 6). In addition, several studies are conducted on standard dimensions of scour protection (Esteban, López-Gutiérrez, Negro, & Sanz, 2019), (CIRIA; CUR; CETMEF, 2007) (Matutano, Negro, López-Gutiérrez, & Esteban, 2013). This information combined with the practical knowledge of the writers is used to define standard dimensions for scour protection. These dimensions are used for further calculations in this report.

Foundation & Scour Protection Characteristics	Offshore Wind Farms				
	Arklow Bank phase 1	Egmond aan Zee	Horns Rev phase 1	Princess Amalia	Scroby Sands
Foundation type:	Monopile	Monopile	Monopile	Monopile	Monopile
Foundation diameter (m):	5	4.6	4.2	4	4.2
Driving length of the pile (m):	35	30	34	30	30
Scour protection type:	Riprap	Riprap	Riprap	Riprap	Riprap
Density of the material used as armour and filter (kg/m ³):	2,600.00	2,800.00	2,600.00	2,800.00	2,600.00
Soil type:	Sand	Sand	Sand	Sand	Sand
Soil median diameter (D ₅₀) (mm):	0.20	0.20	0.15	0.45	0.40
Filter median diameter (D ₅₀) (m):	0.05	0.05	0.20	0.17	0.15
Filter thickness (m):	0.6	0.4	1.00	0.90	1
Filter extension length (m):	20	24	20	24	25
Armour median diameter (D ₅₀) (m):	0.42	0.40	0.55	0.50	0.45
Armour thickness (m):	1.20	1.80	1.80	1.50	1.30
Armour extension length (m):	15	18	15	18	15

Figure 6: Foundation and scour protection characteristics of offshore wind farm case studies (Estaban et al, 2019)

Assumptions for the calculation of scour protection mass

Filter layer diameter	5x monopile diameter
Rock armour diameter	4,5x monopile diameter
Filter layer thickness	0,80 m (0,50m by design and 0,30m installation tolerance)
Rock armour thickness	2,00 m (1,50 m by design and 0,50 m installation tolerance)
Amour and filter layer rock density	2650kg/m ³

The surface area of the MP on the seabed is extracted from the Rock armour surface because within that MP surface no rock armour is placed.

Porosity within the filter layer	0,62	38% porosity
Porosity within the armour layer	0,62	38% porosity

5

Scour protection mass



5. Scour protection mass

Among the decommissioning alternatives discussed, the "only scour left" (appendix 1) alternative is generally the most beneficial for nature. This chapter, therefore, aims to create insights in the amount of scour protection that is and will be placed on the seabed. These values are essential to estimate the costs of removing the scour protection. To compare the "only scour left" and the complete removal alternative, a set of standard dimensions, key values and assumptions are made representative for Dutch North Sea wind farms.

In this chapter the scour mass is calculated for 4 scenarios. The first is based on the wind farms that are currently in operation or in preparation until 2026. The data of these wind farms is to a certain extent known by the authors. The second scenario estimates the future scour volumes in the Dutch waters installed up to 2050. The third, scenario focusses on the scour protection installed in the North Sea in 2050 to provide a broader perspective of this topic. It should be noted that the estimations for the future scenarios have a significant larger fault margin because many data points are based on assumptions. However, it can kick-start the discussions globally about the connection between ecological, material, and financial costs and benefits of scour protection removal and the use of it near wind turbines.

5.1 Constructed and tendered wind farms in the Dutch North Sea

All constructed wind farms and tendered wind farms are taken into consideration to calculate the current amount of scour protection placed in the Dutch North Sea. The dimensions of the wind farms are listed in table 2. The monopile diameter is not always the same within a single wind farm, the diameter mentioned in the table is an estimation of the mean diameter based on open available knowledge. For wind farm Egmond aan zee and Amalia the data is publicly available. (See chapter 4.2) A few assumptions need to be mentioned by the authors:

Assumptions for the current wind farms in the Dutch North Sea

- For wind farms without publicly available data, estimations from chapter 4 are used
- Wind turbines at Hollandse Kust West VI and VII are estimated to be 14MW
- Design values + installation tolerance assumptions from chapter 4 are used to calculate the mass
- All scour protection of the windfarms to be decommissioned shall be removed

Table 2: Dutch offshore windfarm dimensions

Date of construction	Wind Farm	Developer	Turbines	Total MW	MW per turbine	Monopile Diameter
Expectation 2026	Hollandse Kust (West) VII	Oranje wind power II (RWE AG)	55	760	14	8,5
Expectation 2025	Hollandse Kust (West) VI	Ecowende (Shell, Eneco)	55	760	14	8,5
Expectation 2024	Hollandse Kust (Noord) V	Crosswind (Shell, Eneco)	69	759	11	7,5
Expectation 2023	Hollandse Kust (Zuid) IV	Vattenfall	35	385	11	7,5
Constructed 2023	Hollandse Kust (Zuid) III	Vattenfall	35	385	11	7,5
Constructed 2022	Hollandse Kust (Zuid) II	Vattenfall	35	385	11	7,5
Constructed 2022	Hollandse Kust (Zuid) I	Vattenfall	35	385	11	7,5
Constructed 2021	Borssele V	Octopus Energy Generation	2	19	10	7,5
Constructed 2020	Borssele IV	Blauwwind (Shell, Eneco, Luxara, Inpex, Swisslife, Partners Group)	40	380	10	7,0
Constructed 2020	Borssele III	Blauwwind (Shell, Eneco, Luxara, Inpex, Swisslife, Partners Group)	37	352	10	7,0
Constructed 2020	Borssele II	Orsted	47	376	8	8,0
Constructed 2020	Borssele I	Orsted	47	376	8	8,0
Constructed 2015	Gemini	Northland Power, Siemens, HVC, Alte leipziger halleisches	150	600	4	7,0
Constructed 2015	Luchterduinen	Eneco	43	129	3	5,0
Constructed 2008	Prinses Amalia	Eneco	60	120	2	4,0
Constructed 2006	Egmond aan Zee (OWEZ, Q7)	Shell	36	108	3	4,6

5.2 Planned wind farms in the Dutch North Sea in 2050

The Dutch Government wants to ensure society becomes more sustainable in time to meet the 2050 net zero goals. That is why the Government is focusing on the generation of wind energy at sea up to approximately 70 GW in 2050 (Rijksoverheid, n.d.). The total scour protection mass and volumes can be calculated using the following assumptions.

Assumptions for Dutch OWF installed in 2050

- 72.000MW is installed in 2050
- Only Monopiles are used as foundation type
- Double layer scour protection, like current installed wind farms
- Monopiles have an average diameter of 11 meters
- Mean turbine capacity is 25MW
- All scour protection from decommissioned wind farms is removed

5.3 Planned wind farms in the complete North Sea in 2050

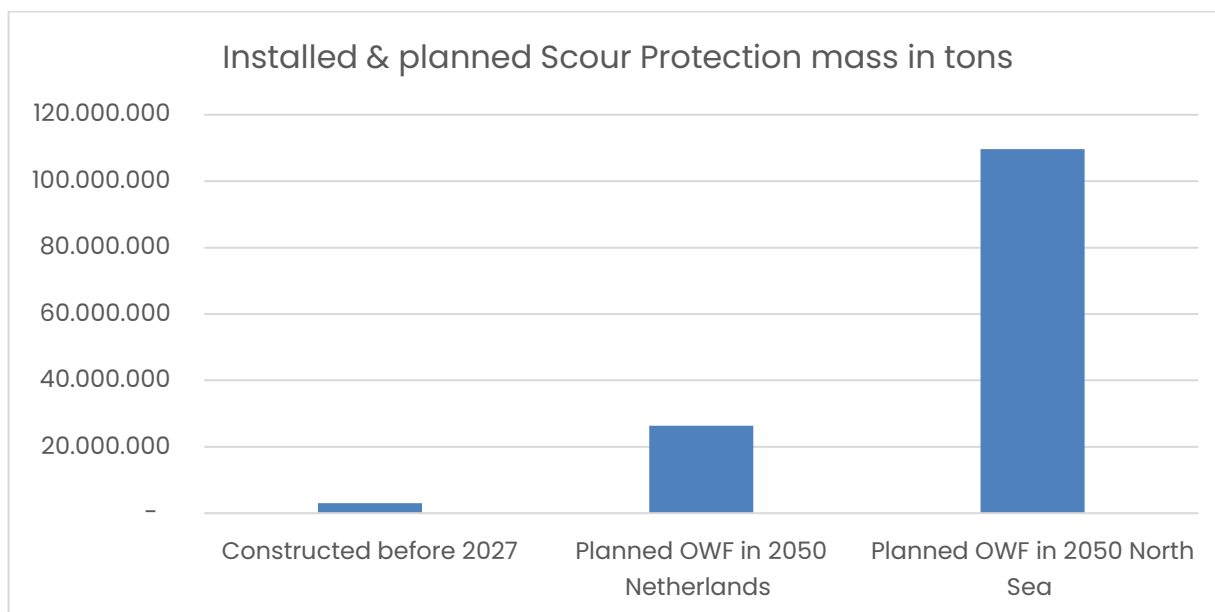
The North Sea holds a vast offshore wind energy potential. Offshore wind is one of the key building blocks for the green transition of Europe and to meet the Paris Climate Goals. This is reflected by the 2050 capacity target of 300 GW set by the European Commission. With a set of assumptions, the volumes and mass of scour protection can be calculated in the North Sea in 2050.

Assumptions for North Sea OWF installed in 2050

- 300.000MW is installed in 2050
- 80% Monopiles are used as foundation type
- 10% jackets are used as foundation type
- 10% Floating are used as foundation type
- Scour protection is a double layer riprap, like current installed wind farms
- Monopiles have an average diameter of 11 meters
- Mean turbine capacity is 25MW
- At jackets more scour protection is expected, while at floating less scour protection is expected. Therefore, monopile scour volumes are used for both foundations to level this
- All scour protection from decommissioned wind farms is removed

5.4 Values

Currently, roughly 3 million metric ton of scour protection is installed in the Dutch coastal waters. This will increase to approximately 26 million metric ton by 2050. The North Sea ecosystem does not stop at borders, therefore an estimation of all turbines in the North Sea gives a total scour protection installed by 2050 of approximately 110 million metric ton. For comparison reasons, this is the same weight as 10.891 Eiffel-towers. That is more than 1 Eiffel-tower each day from today to 2050.



6 Costs of scour protection removal



6. Costs of scour protection removal

The differences in cost between leaving scour protection behind compared to complete decommissioning can be calculated by estimating the costs of scour protection removal. Currently removal of scour protection is mandatory, therefore leaving the scour protection behind can be seen as saving the expenses of removing it. These savings are beneficial for the wind farm developer if no commitments to leaving the scour protection behind are addressed by the government. For the cost calculations, such commitments are not speculated.

Above mentioned topics are strongly influenced by the contract conditions between the developer and the contractor. In the cost calculations a lower and upper boundary is calculated. In the next chapter contract conditions are shortly explained.

6.1 Contract conditions

Offshore contractors are heavily depending on vessel availability. The availability will determine when the decommissioning operations can be done, comprising a large amount of the costs. The contractor will most likely invoice costs for mobilization and demobilization (mob-demob) of the required vessels. This includes crew change, sailing to the project and project specific preparation of the vessel and is estimated to be 19% of the total costs according to a study by the UK government (Climate change Capital) . However, if the contractor and operator can agree on a flexible timeframe (for instance 2 years) in which they can remove the scour protection, then they might invoice less to no mob-demob costs, as they can use the vessel during periods of less works or in-between other jobs.

This flexibility has another advantage for the contractor. It is estimated that rock armour materials can be sold for a percentage of its original price. They can sell the rock armour and use it in another project (after certification) without having to store the materials which is deemed very expensive and time consuming. There are other potential flexible contract options like removing all scour and store it at one location under water as a temporary depot before re-use in another project. All these potential agreements will create an upper and lower boundary of costs related to the scour protection decommissioning.

Also, it should be noted that the distance to shore, scour protection mass, detail of decommissioning and rock armour construction can greatly influence the costs. For these, standard dimensions are used as described before.

At last, the cost calculated in this chapter don't include any vessel delay. The most common delay originates because of adverse weather. The contract will include conditions to have this financially covered by the operator (especially at the fixed date contract). Also, technical or HSE malfunctions delay can be encountered at the vessel. The costs mentioned in this report are therefore optimistic and cannot be used to calculate the costs of a certain project. The differences in contract conditions are summarized in below box for a flexible and fixed date contract.

Flexible (more cost efficient)	Fixed date (higher in cost)
• Flexible date of decommissioning • Less to no mob-demob costs • No storage of scour protection • Optimization of reusing scour protection • Flexibility in weather delay	• More expensive operation costs • High mob and demob costs • Transportation and storage costs of scour protection • Weather delay risks in contract will increase the price

6.2 Additional calculation impact factors

To calculate the costs of scour protection removal, other impact factors are considered. Those are mentioned below.

Impact factors

- Scour is often removed 24 months after monopile removal.
- For the calculation a static scour protection is assumed. Meaning that all stones are within a meter of the installation records.
- Substations, cable crossings and cable routes are not considered.
- Storage of scour on land and associated costs are not considered.
- Spring 2023 prices are used for fuel, rock, equipment, labour, etc.
- A filter layer covers the entire diameter, whereas for rock layer, the diameter of the monopile is subtracted.
- For the installed filter layer 30cm of extra rock is assumed than the design values, for the rock armour layer this is 50cm.
- Second-hand value of removed rock must be determined by grading the stones after passing through a sieve.
- The revenue of second-hand rock is assumed to be 50% of its new price.
- Activities to reduce the negative environmental impact effects on among others. turbidity and noise may affect the cost of scour removal and are not considered.
- Reasonable assumption is that stones may be deposited elsewhere, making scour removal cost-effective.
- A maximum distance of 50 nautical miles is assumed for stone transport.
- Rock Armour is removed with a wire crane on a jack-up vessel and transported by barges including the costs of the transport 50 miles and unloading at harbour.
- An in-survey, out-survey and ROV inspection is calculated.
- Filter layer is removed by a TSHD with self-unloading possibility including the costs of 50 miles transport and unloading at harbour.
- Contractor general cost + revenue + risks are not integrated in the calculation.
- P0 is calculated so no weather delay.
- No technical or safety delay is considered.

6.3 Decommissioning costs for an average installed or tendered Dutch wind farm

As stated before, costs are highly variable depending on multiple factors. In chapter four, five and six, the research has explained all these impact factors. These are used to calculate the costs in a detailed level. The researchers recommend reading those chapters before using below mentioned values.

The costs of decommissioning a large wind farm will be cheaper per metric ton scour protection than the cost of removing smaller wind farms. This is based on among others the Mob-Demob costs and room for optimization in the process. The researchers calculated the costs by taking the current average Dutch Wind farm (based on table 2), which has approx. 49 turbines.

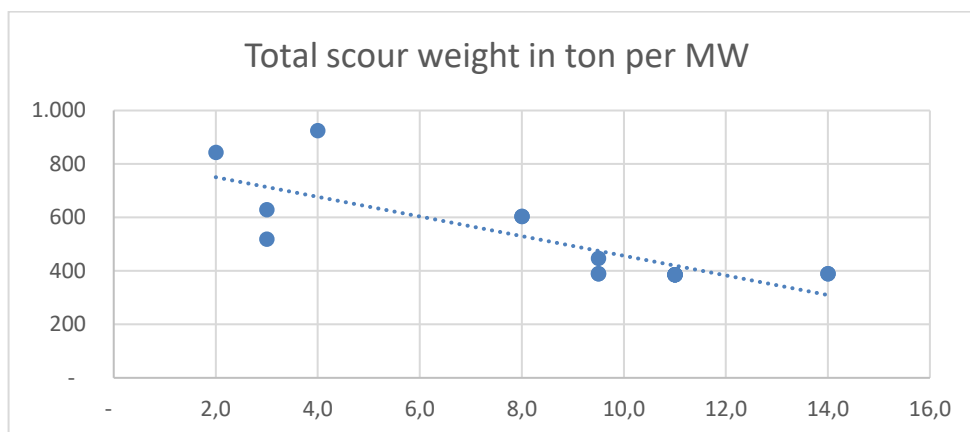
The decommissioning costs for scour protection of the average Dutch Wind Farm is calculated to be approximately 10 million euros.

Dividing this value by the average volume of stones at these windfarms gives the decommissioning costs per metric ton, which is calculated to be approximately 50 euros.

6.4 Trends & insights

Scour weight in ton per MW

By increasing the monopile diameter, more scour protection is calculated. The bigger monopiles also carry turbines with a higher capacity. The researchers calculated the scour protection weight per MW by plotting the turbine capacity on the X-as and the scour volumes divided by its capacity on the Y-as. It can be concluded that based on the Dutch wind farms, less scour protection is needed per MW when installing bigger wind turbines.



Filter and Armour layer differences

During the calculations, the researchers found that removing the armour layer is approximately 20% more expensive per metric ton than removing the filter layer. However, this greatly depends on the different armour and filter grading, classes, and layer thickness.

- For instance, at some OWF's 2-63mm filter layer gradings are installed, while at other OWF's 10-60kg grading is installed. This will give a difference in decommissioning method and therewith the costs.
- In some cases, the armour layer is 4 times thicker than the filter layer while in other cases the filter layer was 2 times thicker than the armour layer. This influences the method and time of decommissioning and therewith the costs.

The consistent factor is that the total mass (filter + armour) is close to the assumed values that are used in this research. But a 20% deviation from the average euro/ton should be assumed to give an estimation that is fair for most wind farms. In the cost calculations below the researchers have used their assumptions as described earlier.

Cost relation between current and planned wind farms

During the calculations, the researchers found that future wind farms will be built further from the coast and in deeper waters. This will increase the costs of the decommissioning. On the other hand, those wind farms have more turbines and have therefore a reduced mob/demob percentage in their cost calculations. Other factors like volume per location, optimization in decommissioning, scour protection size, vessel size/costs and weather conditions further from shore can all influence the cost calculation of future wind farms. The researchers have performed multiple scenario analysis. However, no clear trend can be drawn from these analyses. Therefore, the more substantiated cost per wind farm and per metric ton are also used for the decommissioning cost estimation for future wind farms.

6.5 Total offshore decommissioning costs

The costs are calculated, considering the mentioned trends, the mass values of chapter 5 and the cost calculations from chapter 6.

Between €125 and €188 million is needed to remove all scour protection in the current Dutch tendered or installed wind farms. This will increase to approximately €1.089 and €1.633 million by 2050 in the Netherlands alone. The North Sea ecosystem does not stop at borders, therefore an estimation of all turbines in the North Sea gives a total cost to remove scour protection by 2050 of approximately €4.537 and €6.806 million. This is comparable with the investments in a new 4GW offshore wind farm at the North Sea.

The decommissioning costs for all scour protection installed in the North Sea in 2050 will cost between €4.537 and €6.806 million.

7 Conclusion and recommendations



7. Conclusion and Recommendations

What alternative decommission scenario would be the most feasible instead of the current complete removal policy?

The "only scour left" alternative is beneficial for nature, by leaving natural substrate behind. It involves removing only the monopile while leaving the scour protection, resulting in shorter and less intense decommissioning activities at sea. This approach minimizes temporary disturbances to the marine environment, potentially qualifying the area for designation as a protected area due to its established natural values, which could effectively prevent the return of bottom-trawling fisheries. Preserving undisturbed epifauna on the scour protection is a key consideration for stakeholders in this discussion. The risks associated with this alternative are lower than when part of the monopile is left behind.

Removing the natural values that have been established during the lifetime of the windfarm, only to potentially replace them with artificial reefs for nature development during the permitting process for a new windfarm (repowering), would be contradictory. It is crucial to thoroughly assess the ecological values that have emerged in each specific location, making them the paramount factor in decision-making. To ensure an impartial evaluation, this assessment could be delegated to an independent scientific committee. This approach guarantees that decisions are based on rigorous scientific analysis and avoids setting precedents for future actions.

Could offshore wind farm developers invest more in nature with the saved expenses compared to complete decommissioning?

This report highlights that the removal of scour protection for a current Dutch wind farm requires an average expenditure of 10 million euros. By leaving the scour protection intact, offshore developers can view this amount as cost savings. However, it can be argued that these expenses were already factored into the original business case and could be reconsidered for alternative purposes.

An incentivized approach could be adopted, wherein operators are motivated to strive for the preservation of natural values throughout the wind farm's lifespan, reducing the need for decommissioning. For instance, a potential model could involve a 90/10 split, where operators receive 10% of the "profit" generated from achieving such natural values. Moreover, this fund can be used not necessarily limited to the specific wind farm, but rather towards an (inter)national public/private fund or monitoring program. This would allow the allocated funds to be utilized for various purposes to enhance the biodiversity and knowledge about it. It could be debated that once these actions are taken, the responsibility of the operator of the site would no longer be applicable.

Environmental impact

Imposing a mandatory clean-up obligation may result in generating more waste compared to leaving the scour protection intact. The removal process entails several potential negative consequences, such as increased greenhouse gas emissions from ships, water column turbidity caused by the removal operation, operational risks including oil leakage from vessels, and the significant and irreparable impact on the benthic ecosystem surrounding the scour protection.

Damage by monopile extraction

It is important to acknowledge that the extraction of the monopile (cutting below the seabed) will impose significant pressure on the wildlife inhabiting the scour protection. Extensive research is necessary to comprehend the potential ecological consequences, including the potential recovery of the natural habitat and the resilience of species affected by the monopile removal and the retention of the scour protection. Understanding the long-term impacts and species survival under these circumstances is crucial for informed decision-making.

Considerations when decommissioning filter or armour layer scour protection

There are significant differences in the decommissioning process between the filter layer and the rock armour layer at offshore wind turbines, mainly due to the variation in size of the materials used.

The filter layer, located at the bottom, often consists of smaller particles ranging from 2 mm to 63 mm in size. Removing this layer completely is challenging and costly due to the small size of the particles. Achieving 100% clean-up of the filter layer is unfeasible and difficult to prove. Excavating a large area is the only way to ensure complete removal, but this approach is not only highly expensive but also results in the removal of a substantial portion of the seabed. Moreover, due to differences in material homogeneity, it is uncertain how effectively the mix of filter layer and sand from the seabed can be reused. Therefore, alternative applications such as sand supplementation are excluded.

In contrast, the rock armour layer, composed of larger stones, is comparatively easier to clean up to a reasonable height. These stones can be reused, with a distinction between high-quality (certified) and low-quality (non-certified) applications of rock armour. Transporting rock armour to land is not considered cost-effective. Instead, a more realistic scenario involves storing the stones in an underwater depot or directly reusing them at another project location.

How the costs should be interpreted

This report gives a first look into the general costs of removing the scour protection. All assumptions are transparently mentioned, and the costs are calculated in detail. However, factors like weather conditions, contract conditions and site-specific conditions could not be integrated. In practice, the chances are that the costs may double because of the weather and contractual conditions. Therefore, the values in this report should only be used as a certain orientation. Parties should perform site specific calculations to understand their costs.

The reason why costs are mentioned in this report is to give an orientation and to challenge the readers to think about the millions of euros, the years of work and the long-term effects on the environment. Scientific experts, governments and industry partners should come together to share their knowledge and to find the best solutions for decommissioning of scour protection.

Final words

Decommissioning of wind turbines, the foundation and all related infrastructure is a topic that should be discussed with a comprehensive approach that is not only focussed on the economic side but also on the environmental effects, the circularity targets and human capital efforts. The transition to a circular and sustainable world can be achieved by transparency and collaboration between the stakeholders, good luck!

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Appendix 1: Different phases of offshore wind decommissioning¹

Complete removal

In this alternative, the seabed is 'left as it was found', as the monopile is completely removed along with the surrounding scour. In discussions with contractors, uncertainty was expressed about how to completely remove a monopile in the North Sea. An often-mentioned concept is 'reversed installation technique' in which every part from top to bottom is removed piece by piece and mirrored to the installation order. Scour may be removed first by using a grab-vessel. Dredging activities (i.e., removing surrounding soil) can be used to enable attachment of lifting equipment to the pile (Topham & McMillan, 2017). Although Kerkvliet and Polatidis (Kerkvliet & Polatidis, 2016) state that foundation structures are commonly removed in full by using explosives, a report by TNO (TNO, 2020) elaborates on other technologies that are currently under development: hydraulic (pressurizing the monopile to force it loose) and vibratory (using vibrations to overcome friction between soil and monopile) removal. Yet there still exists uncertainty about applying these methods on the open seas.

Partial removal

In literature, 'Partial removal' often refers to cutting the pile a few meters below the seabed, leaving the remaining sub-seabed part in situ (Kerkvliet & Polatidis, 2016; Smyth, Burdon, Atkins, Barnes, & Elliott, 2015). In this study, also alternative partial removal strategies were examined: topping, leaving only scour in place and using a designated reefing area. These alternatives have previously been described for the oil and gas (O&G) industry (Sommer, et al., 2019). In all partial removal alternatives, the monopile is cut, for which internal cutting is expected to be most cost-effective (Gjødvaad & Ibsen, 2016; Kaiser & Snyder, 2010; Kerkvliet & Polatidis, 2016). Contractors confirmed that most likely the monopile will be cut from the inside out.

A. Cutting below seabed

In this alternative, the monopile is cut approximately 4 to 5 meters below the seabed. As with full removal, it is expected that scour protection is removed by dredge-and-grab activities. Part of the monopile is left behind yet will no longer be noticeable after the seabed is resettled (Teunis, et al., 2021).

B. Topping

'Topping' includes cutting the monopile a few meters above the seabed, thereby leaving scour in situ (Fowler, et al., 2020). In this assessment, it is assumed that the monopile is cut 2 meters above the seabed, yet other heights are also plausible (Fowler, et al., 2020).

¹ Note: The appendix has been adopted from the report "Providing room for nature in decision-making for decommissioning offshore wind foundations" (Jurrius, 2021). This research was carried out as part of a master thesis for the Vrije Universiteit of Amsterdam and supervised by ECHT. The author and ECHT have reached a mutual agreement regarding the utilization of these materials in this research.

C. Only scour left in place

This alternative involves below seabed cutting or complete removal of the monopile (foundation) but leaving scour in situ. This is deemed a plausible scenario and has been already mentioned in Danish decommissioning plans. The reasoning to execute this alternative includes reducing both environmental consequences and technical complexities.

D. Designated reefing area

'Reefing' involves repositioning structures elsewhere, to be purposefully deployed as an artificial reef (Sommer, et al., 2019). Fortune & Paterson (Fortune & Paterson, 2020) argue that this provides the possibility to deliberately create a thriving reef in a suitable and preferred area. In this assessment, it is assumed that the monopile is cut below seabed and the retained steel and scour are deposited in a designated reefing area. Due to lack of previous experiences, this study assumes that the DRA covers an area of 1 km².

Marine protected area

As an addition to the above-mentioned alternatives of Topping and leaving only scour in situ, the option to designate the site as marine protected area (MPA) after decommissioning is investigated. An MPA is defined by the European Environmental Agency (EEA) as "geographically distinct zones for which protection objectives are set" and are an important attribute in both Dutch and European nature conservation objectives (Weinert, Mathis, Kröncke, Pohlmann, & Reiss, 2021). Multiple categories of MPAs exist, yet it often involves measures to counter "overexploitation of marine resources and degradation of marine habitats" such as a no-take area for fisheries (Weinert, Mathis, Kröncke, Pohlmann, & Reiss, 2021). Since OWFs are exclusion zones during their operational period of circa 30 years, the designation of an MPA could be a practically feasible step (Ashley, Mangi, & Rodwell, 2014). Alternatively, other than designating a site as a marine protected areas "other effective area-based conservation measure areas" are areas that are achieving the long term and effective in-situ conservation of biodiversity outside of protected areas could also be considered.