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Ecological Effects of Offshore Wind Farm Decommissioning within the KEC Framework in the Netherlands

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Abstract

The decommissioning of offshore wind farms is an increasingly important phase in the lifecycle of offshore wind energy, yet knowledge about its ecological impacts remains limited. This report examines the expected ecological impacts of decommissioning offshore wind farms in the Dutch North Sea, with specific attention to the themes within the Framework for Assessing Ecological and Cumulative Effects (KEC) and potential effects on other protected species and habitats. Based on a synthesis of scientific literature, policy documents and interviews with stakeholders, the report describes the key decommissioning processes and scenarios and analyzes the potential ecological consequences for marine ecosystems.

The results demonstrate that decommissioning is ecologically relevant primarily as a transitional period, during which short-term but intensive disruptions occur. The magnitude and significance of these effects depend heavily on the chosen decommissioning strategy, implementation technique, seasonality, and cumulative effects with other offshore activities. The report highlights that decommissioning is currently insufficiently and inconsistently addressed in EIAs and emphasizes the need to explicitly include decommissioning as a separate lifecycle phase in both KEC assessments and EIAs. Applying worst-case scenarios and conducting targeted monitoring before, during, and after decommissioning are identified as essential steps for improving assessment quality. It also emphasizes that the lack of a long-term ecological vision for the North Sea and the absence of ecological baselines pose significant obstacles to a consistent and well-founded assessment of decommissioning impacts. By addressing these gaps, this report offers concrete starting points for improving ecological assessments and developing forward-looking policies for the decommissioning of offshore wind farms.

Keywords: offshore wind farms, decommissioning, ecological impacts, KEC, cumulative effects, monitoring, North Sea

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1. Introduction

1.1 Background

The global energy transition needs a rapid upscaling of renewable energy, with wind energy playing a leading role (Hall et al., 2020). This also plays a very important role in achieving the Netherlands 2050 climate targets (Nortier et al., 2020). Although the construction, operation and decommissioning of offshore wind farms (OWFs) have increased significantly in recent years, the ecological impact on the North Sea system has only been partially investigated (Gușatu et al., 2021). This limited understanding is becoming more urgent now that the first generation of Dutch OWFs is approaching the end of its technical life in 2030 and will have to be decommissioned in the relatively short term. Decommissioning is the phase in which foundations, cables, and associated infrastructure are removed or partly removed. This therefore constitutes a new, essential part of the life cycle of OWFs, with potential ecological consequences that have hardly been taken into account in policy frameworks or monitoring programs (Demuytere et al., 2024).

Although more is now known about the effects of the construction and operational phases, there is still little scientific clarity about the possible ecological consequences of the decommissioning of OWFs. Decommissioning activities may generate direct and potentially harmful environmental effects, including underwater noise from cutting or extracting turbine piles, increased sediment disturbance, temporary turbidity, and higher levels of vessel traffic.

At the same time, these impacts interact with the fact that OWFs alter the North Sea ecosystem by introducing hard substrates into a predominantly sandy seabed (Stranddorf et al., 2026). These structures are quickly colonized by marine organisms and function as artificial reefs, which can lead to increased local biodiversity (Degraer et al., 2020; Galparsoro et al., 2022; Stranddorf et al., 2026). The complete removal of these elements at the end of their life cycle can therefore lead to the loss of ecologically valuable habitats. At the same time, the preservation of structures can promote the spread of non-native species or alter ecosystem functions (Stranddorf et al., 2025). The balance between these short-term disturbance effects and the loss of ecological functions created during the operational phase is still poorly understood, forming an important knowledge gap.

The scientific foundation for ecological impact assessments within the Framework for Assessing Ecological and Cumulative Effects (KEC) in the Netherlands is provided by initiatives like the Offshore Wind Ecological Program (Wozep) and the MONS program (Kader ecologie en cumulatie, 2025; MONS, 2025; Wozep, 2025). OWF construction and operation are currently partly taken into account by KEC (Wozep, 2025). However, decommissioning has not yet been included, despite possible consequences such as underwater noise, temporary disruption by shipping, habitat loss, sediment disturbance and changes in food web dynamics. This creates a big knowledge gap here. To improve Environmental Impact Assessments (EIAs), support adherence to international biodiversity commitments and strengthen KEC evaluations, it is important to identify pertinent ecological considerations early on.

During this project with Rijkswaterstaat, the ecological implications of the decommissioning (removal) phase of North Sea OWFs in the Netherlands will be investigated. The project is part of Wozep, the program has a broad range of research themes, including bird and bat interactions, marine mammals and the underwater noise impact, benthos, fish and electromagnetic fields, ecosystem effects, and lastly data and information management (Wozep, 2025).

1.2 Problem statement

The KEC assesses the ecological impacts on protected species in consideration of the entire planned roadmap of Dutch OWFs is based on the latest scientific knowledge and modeling estimates, an example of the Offshore Wind Roadmap, as presented in KEC 5.0, is shown in Appendix 1. (Kader Ecologie en Cumulatie, 2025). These assessments now include the preparation phase (e.g., surveying on location and clearance of unexploded ordnance), the construction phase (e.g., underwater noise from pile driving during turbine installation), and the operational phase (e.g., bird collision on turbines and potential loss of habitat) (Kader Ecologie en Cumulatie, 2025). Decommissioning is not yet included in these assessments. It must be observed that the decommissioning phase, in which the end-of-life operating phase of the OWFs is attained and they are dismantled, could also have environmental effects to be incorporated in an orderly manner in the evaluation framework.

Additionally, decommissioning is currently given little attention in EIAs. In EIA assessments, the focus remains on construction and operation, while end-of-life impacts are often only briefly described. Because so few OWFs have been completely decommissioned to date, there is still a shortage of empirical research and documented ecological data, which contributes to this gap in both KEC and EIA assessments. The scientific understanding of the effects of decommissioning is still evolving due to the small number of international cases and the variety of methods employed in those projects. In order to ensure that decommissioning is assessed, managed, and regulated on the basis of ecological knowledge, it is important to close these research gaps as OWFs in the Dutch North Sea approach the end of their operational lifetime.

1.3 Scope

This study examines the potential ecological effects of decommissioning OWFs in the Dutch North Sea, with specific attention to the themes addressed in KEC. The analysis focuses on the removal process itself: how decommissioning is expected to take place in the coming decades, which techniques are likely to be applied to foundations, cables, scour protection, and high voltage offshore platforms, and what ecological effects this may include.

The project explicitly excludes nature inclusive construction and the creation of natural values at OWFs during the operational phase, as well as the ecological consequences of the disappearance of these values during removal. The scope is therefore limited to identifying decommissioning related disturbances, such as underwater noise, sediment disturbance, loss of hard substrates, increased shipping activity, and temporary habitat changes, and linking these disturbances to the relevant KEC themes and protected species groups.

1.4 Research aim

This project will focus on exploring the potential ecological impacts of OWF decommissioning, with specific attention to the themes addressed within the KEC framework as well as potential impacts on other protected species. If decommissioning activities affect additional species, these may also need to be considered to avoid missing important ecological aspects. The main aim is to provide input for improving KEC assessments, but also to support better evaluations in EIAs and to identify knowledge gaps that could guide future research. The focus is on the decommissioning process itself: how this process is likely to be carried out in the future, which techniques are expected to be applied, and what ecological consequences may result. It should also be noted that the scope and extent of decommissioning will partly depend on future political choices regarding the dismantling and clean-up of OWFs.

1.5 Main research question

The main research question for this project is:
What ecological effects can be expected during the decommissioning of offshore wind farms in the Dutch North Sea, and how can these insights improve KEC assessments, strengthen EIAs, and help identify critical knowledge gaps for future research?

1.6 Sub questions

Decommissioning process

- What are the anticipated procedures and stages involved in the decommissioning of OWFs?
- Which techniques (e.g., cutting, pulling, vibrating, explosive removal) are expected to be applied to foundations, cables, and transformer platforms?
- What documented international experiences from countries such as Denmark, the United Kingdom, and Germany exist, and what specific lessons can be identified from these cases?

Ecological effects per KEC theme
Birds and Bats

- Which specific disturbances and risks, including increased shipping activity, artificial lighting, and habitat loss, are anticipated during the decommissioning phase?
- How do the ecological effects observed during decommissioning differ in magnitude and nature from those documented during the construction and operational phases?

Marine mammals
- What effects could underwater noise and vibrations during decommissioning have on harbour porpoises and seals?
- How severe and long-lasting are these effects compared to the construction phase?

Marine life (benthic fauna, fish, reef ecosystems)
- What are the consequences of removing hard substrates (foundations, scour protection) for local biodiversity?
- What is the magnitude and ecological significance of temporary sediment disturbances on benthic organisms and fish populations, both near the OWFs and along the cable routes?

Indirect and cumulative effects
- What are the potential ecological consequences if multiple OWFs are decommissioned in the same period?
- How similar does the ecosystem become to its original state once an offshore wind farm has been removed?

Uncertainties
- How can the KEC framework account for uncertainties and knowledge gaps related to decommissioning when incorporating this phase into future KEC assessments?

To answer the research questions, the project will combine findings from literature reviews with stakeholder consultations. In order to gain a broad picture of decommissioning, it is important to survey stakeholders from different perspectives so that all angles can be examined. This includes stakeholders from the market, NGOs, contractors, and OWF owners. To ensure that OWF decommissioning practices elsewhere are considerd and relevant environmental consequences are assessed, consultations will also be conducted with other relevant organizations and authorities in the United Kingdom, Germany, Belgium, Denmark, and Norway. This multi-actor approach will provide a robust basis for analysis of future ecological impacts relevant to the inclusion of decommissioning within future KEC and EIA assessments.

2. Legal Framework

2.1 International Legal Framework

Four major international regimes shape decommissioning practices: the United Nations Convention on the Law of the Sea (UNCLOS), the International Maritime Organization (IMO) Guidelines, the OSPAR Convention, particularly OSPAR Decision 98/3 and the London Convention/Protocol. Although these frameworks were originally written primarily for oil and gas (O&G) installations, they now indirectly provide guidance for OWF decommissioning.

UNCLOS
The general legal framework for maritime operations is provided by UNCLOS. UNCLOS Article 60(3) declares: *"Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent international organization."* (UNCLOS, 1982).

This article establishes three principles: (1) removal is required; (2) removal promotes navigational safety; and (3) adherence to globally accepted standards is required. These standards are further shaped by the IMO and OSPAR regimes (De La Fayette et al.,1996; Ringbom et al., 2018).

It is important to note that UNCLOS on purpose leaves room for interpretation. The obligation to remove offshore installations is formulated in general terms and does not prescribe a uniform or detailed regulations of removal. This flexibility reflects the nature of international treaties. Treaties are inherently difficult to establish or amend, especially when they have been signed by a large number of states. By working with broad principles rather than detailed technical regulations, UNCLOS enables states to apply the core principles to a wide range of offshore installations, including technologies and structures that did not exist at the time the Convention was drafted. This gives national authorities the policy space to interpret and apply Article 60(3) in a way that is consistent with changing technical, environmental, and regulatory circumstances.

IMO
Article 60(3) is operationalized by the IMO 'Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone' (1989). The guidelines outline circumstances for partial removal and restate a general rule of complete removal. They make it clear that: *"Abandoned or disused offshore installations or structures on any continental shelf or in any exclusive economic zone are required to be removed, except where non-removal or partial removal is consistent with the following guidelines and standards."*

The IMO lists explicit criteria that must be assessed in the case of partial removal, including technical feasibility, environmental impacts, risks of shifting materials, and long-term navigational hazards.
Although these guidelines are recognized globally, they are not legally binding. This again leaves room for national interpretation.

OSPAR
The OSPAR Convention (1992) is a legal framework in the North-East Atlantic region. Annex III, Article 5 (1,2) on disposal of offshore installations states that: *"No disused offshore installation or disused offshore pipeline shall be dumped and no disused offshore installation shall be left wholly or partly in place in the maritime area without a permit issued by the competent authority of the relevant Contracting Party on a case-by-case basis. [...]''*

OSPAR Decision 98/3 forbids the disposal or retention of offshore installations. The decision specifies: *"The dumping, and the leaving wholly or partly in place, of disused offshore installations within the maritime area is prohibited."* was adopted in 1998 and was explicitly drafted for O&G installations, the dominant offshore industry at that time. The decision does not explicitly mention offshore renewable energy, and when it was written, commercial offshore wind did not yet exist in the North Sea.

As a result, the formal applicability of OSPAR 98/3 to OWFs is legally ambiguous. Several Contracting Parties have acknowledged that the decision's scope does not neatly extend to OWFs, and discussions are currently underway within OSPAR working groups to determine whether the convention should be updated or expanded to explicitly cover offshore renewables. Until such revisions are made, it remains uncertain to what extent OSPAR 98/3 is legally binding for wind turbines.

Despite this ambiguity, the underlying principle of 98/3 is still informative: *"Leaving structures in place should be the exception rather than the rule, and any deviation from full removal requires strong justification and a comparative assessment."*

The existing derogation regime designed for heavy O&G structures, such as gravity-based concrete platforms, illustrates that exceptions are possible but must be substantiated through a strict Comparative Assessment, as outlined in Annex 2 of Decision 98/3. In practice, many governments use OSPAR 98/3 as a normative benchmark, even while acknowledging that its legal applicability to offshore wind remains under debate.

London Convention/Protocol
The London Convention (1972) and the London Protocol (1996) constitute the global framework prohibiting the dumping of waste at sea. The relevant implications for OWFs are that installations or foundation remains left in situ are legally considered "dumping," unless exceptions are applied (De La Fayette et al.,1996). The London Protocol contains clear prohibitions on abandoning structures unless a state explicitly grants a permit under the permit system, similar to OSPAR. This regime thus reinforces the international norm that abandonment should be the exception, not the standard.

Regional and European environmental law
In addition to removal obligations, OWF decommissioning must comply with EU environmental directives that protect marine ecosystems:

- The Habitats Directive, safeguards Natura 2000 sites and species.
- The Birds Directive, governing effects on avian species.
- The Marine Strategy Framework Directive (MSFD), requiring "Good Environmental Status" (GES).
- The Environmental Impact Assessment (EIA) Directive, which requires that decommissioning impacts are assessed.
- The Maritime Spatial Planning Directive, requires long-term planning, including end-of-life phases.

These directives require the assessment of underwater noise, sediment disturbance, habitat fragmentation, cumulative effects and ecological recovery, factors especially relevant for decommissioning.

Conclusion
The international frameworks make it clear that *"full removal"* is the basic expectation. This is in line with Dutch legal practice, where full removal is the standard. At that time treaties were written for oil/gas platforms and not yet for OWFs, the regimes are relatively old and not future proof. OWFs did not yet exist when the UNCLOS (1982), London Convention (1972), IMO guidelines (1989), and OSPAR Decision 98/3 (1998) were written. As a result, the legal frameworks do not seamlessly match the scale, numbers, and ecological functions of OWFs. For instance, the initial objective was mainly to stop pollution from O&G structures, dumping, and navigation hazards. This leads to interpretation problems, which are now becoming apparent in discussions about whether or not to remove scour protection and monopolies.

2.2 Dutch Legal Framework

2.2.1 Environment Act and Decree on Environmental Activities

Since the Environment Act came into force, the removal obligation for OWFs has been laid down in the Decree on Environmental Activities (Bal). OWFs are classified as restricted area activities within national waters. Section 7.2.3 of the Bal specifies that the entire installation, including turbines, foundations, infield and export cables, scour protection, and offshore substations, must be removed after the end of its use (Bal, 2020).

Pursuant to Article 7.45 (Water: removal of wind farms) of the Activities Decree (Bal), an OWF or OWF export cable that is no longer in use must be completely removed in order to fulfill the social functions of the North Sea (Bal, 2020). This means that all parts of the OWF, including foundations, cables, and scour protection, must be removed. In addition, the Bal stipulates that any material that has ended up on site or in the immediate vicinity during construction, maintenance, use, or removal must also be removed. Dutch legislation therefore does not allow for any parts of the OWF to be left on the seabed.

This obligation also includes the restoration of the seabed, insofar as this is necessary to approximate the original morphological situation. The exact method of implementation is set out in an implementation plan (Art. 7.38 Bal) that must be drawn up by the permit holder and approved by Rijkswaterstaat (Bal, 2020). The removal techniques, risk management, and planning must all be covered in this implementation plan.

2.2.2 Offshore Wind Enegy Act

In addition to the general rules set out in the Bal, the Offshore Wind Energy Act (Wwoz) imposes project specific conditions on the removal phase (Offshore Wind Energy Act Wet windenergie op zee, 2021). Additional obligations may be imposed in the Wwoz permit, for example regarding:

- The depth at which foundations must be cut off.
- How cables are being removed.
- Monitoring and mitigation obligations during decommissioning.
- The period within which removal must be completed.

These conditions supplement the universal obligation under the Bal, so that the national framework contains both uniform requirements and project specific details.

2.3 Dutch Policy Framework

The Dutch marine policy framework for offshore wind energy is set out in a collection of strategic documents and legal instruments, including the 2015 Integrated Management Plan for the North Sea (IBN 2015) and the North Sea Programs. The long-term vision for the sustainable and multipurpose use of the North Sea is outlined in these texts, wherein shipping, energy production, nature, and other spatial claims are rationally balanced against one another. The basic principle of this policy framework is that offshore structures must be completely removed once their lifespan has expired. This national policy principle is closely aligned with international obligations under UNCLOS, the IMO guidelines, and OSPAR Decision 98/3, which together define complete removal as the standard norm.

Although the focus of this policy framework was mainly on the construction and operational phases of OWFs, the current regulatory system under the Environment Act requires that the decommissioning phase also be explicitly included in the planning process. This means that the removal obligation under the Bal forms the legal starting point for assessing ecological and operational effects during decommissioning. An EIA and the plot decision must therefore substantiate the expected (cumulative) effects, for example related to noise, sediment disturbance, soil impact, and the disappearance of hard substrate habitats.

A policy evaluation is currently underway regarding the future of decommissioning within the framework of the North Sea Programme 2027-2033. This discussion focuses on the question of whether complete removal is always desirable or ecologically optimal. This is because of the development of reef like communities on foundations and scour protection, the potential contribution of such structures to biodiversity, and the growing attention to nature enhancement in the North Sea. At the same time, risks relating to shipping safety, future spatial claims, materials in the water column, and the technical and financial proportionality of complete removal are being explicitly considered.

Although this policy process provides insights that may eventually lead to a reassessment of the national removal principle, no decision regarding a policy change has been made thus far. The current policy line is therefore clear: complete removal remains the standard option.

The KEC is an instrument for assessing the ecological cumulative effects of the Dutch offshore wind challenge. Although decommissioning is not currently included in the KEC, the increasing policy focus on the removal phase implies that further integration is necessary. The legal framework of the Environment Act, combined with the policy objectives of IBN 2015 and the North Sea Program, requires a systematic evaluation of:

- Cumulative disturbance from shipping and underwater noise.
- The loss of artificial reef structures and the resulting changes in habitat functions.

- Potential impacts on species protected under the nature conservation activities under the Environment Act.
- Cumulation of removal activities when multiple OWFs are decommissioned within the same period.

Given the large-scale decommissioning task expected towards 2030–2040, the KEC is expected to play an increasingly important role in the ecological assessment, modeling, and policy decision-making surrounding the removal phase of OWFs.

3. Experiences

3.1 National

Despite its strong position in the development and exploitation of offshore wind energy, the Netherlands does not yet have any practical experience with the complete dismantling of commercial OWFs. The legal basis for decommissioning is laid down in the Offshore Wind Energy Act, which stipulates that an OWF that has been taken out of service must, in principle, be completely removed.

According to the Netherlands Enterprise Agency (2025) developers are required to submit a decommissioning plan to the Dutch government, describing the technical method, environmental impact, safety aspects, and logistical implementation. This plan must demonstrate that, at the end of its life, the farm will be left in a condition that corresponds to the original situation.

Dutch legislation requires full decommissioning of OWFs. Under the Activities Decree (Bal), OWFs that are no longer in use must be completely removed, meaning that no components may remain on or in the seabed. Consequently, partial removal or leaving structures in situ is not permitted under the current Dutch legal framework (see chapter 2.2).

Although the Netherlands has not yet decommissioned any OWFs, the first concrete decommissioning processes will take place in the coming years. The Offshore Windfarm Egmond aan Zee (OWEZ), the first commercial OWF in the Netherlands, is to reach the end of its technical life at 31/12/2031, after which approximately two years are planned for the decommissioning phase. The Prinses Amalia OWF will reach this phase earlier, around 2028, also followed by an estimated two-year period for removal operations. These projects will provide the first extensive practical experience and are expected to yield important insights for the further development of technical, ecological, and legal policy on decommissioning in the Netherlands.

3.2 International

International experiences vary between countries relating to decommissioning of OWFs, both in terms of legal frameworks and practical implementation. The differences between countries depend on the age of the OWFs, technological choices, marine spatial context, and institutional traditions.

This chapter discusses the decommissioning practices and experiences of five North Sea countries: Germany, Denmark, Norway, Belgium, and the United Kingdom. This will provide insight into how these countries implement international obligations, national regulations, and operational challenges. This comparison provides a broad picture of the current situation and forms an important basis for understanding the future position of the Netherlands within the international decommissioning context.

3.2.1 Germany

Germany has a mature offshore wind sector, with the first generation of OWFs reaching the end of their technical and economic lifespans. German regulations for offshore wind require licensees to draw up a comprehensive decommissioning plan and remove the installation at the end of the license period. The legal frameworks place a strong emphasis on environmental protection, shipping safety, and responsible material management, and provide for integrated cooperation between developers, regulators, and nature conservation agencies (BWO, 2024). Germany emphasizes in its policy frameworks that decommissioning must be taken into account in the initial project planning so that technical feasibility, costs, ecological risks, and liability remain assured throughout the entire life cycle.

The first concrete case that provides insight into German decommissioning practice is Alpha Ventus, Germany's very first OWF (60 MW, operational since 2010). In 2025, the consortium (Vattenfall, EWE, RWE) decided to completely dismantle the farm because the pilot and research objectives had been achieved and further operation was no longer economically viable (Buljan, 2025a). The decommissioning scope includes the removal of all turbines, jacket and tripod foundations, the offshore transformer station, inter-array cables, and the export cable, followed by transport to land and processing via recycling and reuse (Buljan, 2025b). The German government is involved in the planning phase, with a special focus on environmental impact mitigation, underwater noise, sediment disturbance, and sustainable material flows. The implementation phase is expected to start in 2027–2028 (Memija, 2025).

The decommissioning of Alpha Ventus is therefore a pioneering project that will provide important lessons for future large-scale German OWFs that will also need to be decommissioned within 10–20 years (Casey, 2025).

3.2.2 Denmark

Denmark's national implementation of international decommissioning obligations demonstrates a flexible and case-specific regulatory approach, shaped by the Danish Energy Agency (DEA) and integrated within the country's broader offshore energy legislation (Stranddorf et al., 2026). Danish energy legislation requires that operators to submit a decommissioning plan during the licensing process, however, the law does not require the complete removal of foundations, cables, or scour protection (Stranddorf et al., 2026). This approach aligns with the flexibility inherent in OSPAR 98/3, permitting national authorities to make exemptions when it can be assured that there will be "no adverse impact on the environment, the safety of navigation and other uses of the sea."

The only completed decommissioning of a Danish OWF to date is Vindeby (2017), which was the world's first gravitational based OWF. The DEA permitted the removal of all 11 turbines and associated cables, supplemented with strict post-removal requirements, including:

- Verification that the seabed had been restored to a "satisfactory condition".
- Mandatory environmental surveys immediately after removal and again three years later.
- Sediment analyses demonstrating pollutant concentrations well below HELCOM/OSPAR action thresholds.

Denmark's immediate regulatory focus is not on dismantling OWFs but on lifetime extension, reflecting a strategy to postpone large-scale decommissioning until the 2030s and 2040s. In 2024–2025, several OWFs including Samsø, Middelgrunden, and Nysted, received DEA approval for extended operation, while other sites (e.g., Rønland and Horns Rev 1) are under review for similar extensions. These decisions illustrate Denmark's effort to optimize existing infrastructure and defer the ecological and financial burdens of decommissioning.

As a result, Denmark currently has no active decommissioning inquiries, and national authorities are preparing for a future wave of end-of-life projects rather than implementing them at present.

3.2.3 Norway

Norway still has little international experience with offshore wind. This is mostly because of the O&G industry's dominant position, which has structurally accounted for 35–53% of Norwegian exports since 2000 (Ryggvik, 2015). This meant that new large-scale renewable energy production was not economically urgent (Van der Loos et al., 2021). Only one OWF, the floating Hywind Tampen OWF in 2022, was constructed. Norway currently lacks operational expertise and case studies on the decommissioning of OWFs because it has not constructed any older commercial OWFs.

In Norway, the decommissioning of OWFs is legally governed by international obligations (UNCLOS, IMO guidelines, and OSPAR Decision 98/3), which use complete removal as a starting point. Nationally, this is elaborated in the offshore energy act (*Havenergilov*a), which require developers to prepare a decommissioning plan in advance and provide financial guarantees (Hatlebrekke et al., 2024). Because Norway has hardly built any commercial OWFs to date, there are no detailed technical regulations or practical experience with decommissioning. Therefore, the current regulations are relatively general and are implemented on a project-by-project basis.

3.2.4 Belgium

In Belgium, the decommissioning policy for OWFs is laid down in environmental permits, which require operators to *"restore the site to its original state"* after the concession period, in accordance with the Royal Decree on Environmental Management (VEMA) (2003). This includes removing cables, sawing monopiles to at least two meters below the seabed, and submitting a restoration plan one year prior to decommissioning (Van Maele et al., 2023).

Belgium also lacks operational experience with the decommissioning of large-scale OWFs. Stakeholder dialogue, vision development, and technical research projects are the key features of the country's preparatory phase. When the concession for the oldest OWF (C-Power) expires in 2034, the first decommissioning is expected to begin around 2035 and be completed by 2039 at the latest (Van Maele et al., 2023).

3.2.5 United Kingdom

Decommissioning of OWFs in the United Kingdom (UK) is primarily regulated under the Energy Act 2004, later amended by the Energy Act 2008 and, for Scottish waters, the Scotland Act 2016.

The Blyth OWF, installed in 2000, was the UK's first OWF and the first to be fully decommissioned in 2019 (Skopljak, 2019). Although its scale was limited (two 2 MW turbines), Blyth is an important reference for future large-scale decommissioning projects.

Since the complete dismantling of the Blyth OWF in 2019, the UK has tightened its policy framework for decommissioning. The most relevant updates are included in the Decommissioning Guidance Notes for Industry (2019) for England and Wales and the Offshore Renewable Energy: Decommissioning Guidance for Scottish Waters (2022) (The Scottish Government, 2022). These documents clarify the responsibilities of developers, the required content of decommissioning programs, and the conditions under which exceptions to complete removal are possible (BEIS, 2019). They emphasize that alternatives to complete dismantling can only be permitted when there is evidence that complete removal would be unsafe, ecologically harmful, technically unfeasible, or disproportionately costly. The UK is also introducing mandatory Comparative Assessments, requiring operators to compare all feasible end-of-life scenarios in terms of safety, the environment, technical feasibility, social impact, and costs (Paterson et al., 2018).

In parallel with these policy frameworks, the British government is strengthening interinstitutional coordination on end-of-life planning. The UK Marine Management Organisation (MMO) has set up an interdepartmental working group to align guidelines and develop a strategic national approach, given that more than a third of current OWFs will reach the end of their design life before 2035 (Goldsmith, 2025; Offshore Wind Report, 2025). In addition, alternatives to decommissioning are being actively encouraged: in 2025, Ofgem introduced the End of Tender Revenue Stream framework to enable lifetime extension for technically and economically viable OWFs (Ofgem, 2025). Repowering projects will also be supported from 2025 onwards through reforms to the Contracts for Difference (CfD) system, giving operators financial certainty to renew existing farms rather than decommission them (DENSZ, 2024). These developments demonstrate that the UK is taking an increasingly strategic approach to the end-of-life phase of offshore wind infrastructure, with a focus on sustainability, system planning, and minimizing unnecessary capacity loss.

3.3 Oil and Gas

Throughout the past five decades, the global decommissioning of offshore oil and gas (O&G) installations has undergone significant evolution, with advances in both technical methods and regulatory frameworks. The first offshore installation decommissioning was recorded in the Gulf of Mexico in 1973 (Chen et al., 2024). In the North Sea O&G installations are getting older, which has led to widespread international practice where knowledge about decommissioning methods, logistics networks, ecological impacts, and legal requirements have been developed (Doyle et al., 2008).

International regulation has played a major guiding role in this regard. The OSPAR decisionmaking process, and specifically Decision 98/3, prescribes the complete removal of offshore installations as the norm and only allows partial abandonment in exceptional circumstances. This regulatory context has been shaped in part by incidents in the past, such as the Brent Spar.

The Brent Spar platform in 1995 was a turning point in the historical development of decommissioning of O&G platforms (Zyglidopoulos, 2002). Greenpeace’s protest against the planned deep water disposal of the structure forced OSPAR to reject “rigs-to-reefs” (the conversion of no longer in use offshore platforms into artificial reefs) as an acceptable decommissioning route in the North Sea (Jørgensen, 2012). The Brent Spar incident is also important in a larger sense because it showed that decommissioning is a socially and politically charged process in which public perception, ecological care, and transparency are essential (Jørgensen, 2012). This is highly relevant for offshore wind, where cumulative effects and social expectations regarding circularity and nature conservation are constantly increasing.

Comparison between O&G and OWF decommissioning

Decommissioning in the O&G industry is distinguished by a strong focus on environmental preservation, safety, and total removal. The standard procedure typically involves securing wells ("plug and abandonment"), followed by the dismantling of topsides and the removal or cutting of jacket foundations (Fowler et al., 2014). Over time, various techniques have been developed for the physical removal of structures, including heavy lift vessels due to their ability to remove complete topside modules in a single lifting operation (Day & Gusmitta, 2016). These experiences provide a useful foundation for OWF decommissioning in the future, but it is not entirely transferable. Although removal techniques from the O&G industry can be used for OWF decommissioning (such as cutting techniques (Zawawi et al., 2023)), the scale of the infrastructure differs considerably. Oil or gas platforms are large structures, but relatively limited in number, and typically stand on only four to six supporting piles, which considerably reduces their overall seabed footprint compared to OWFs (Spielmann et al., 2023). OWFs consist of many turbines, which leads to a scaling issue that hardly ever occurs in the O&G industry. Whereas a jacket or a set of monopiles needs to be removed under a platform, an OWF dozens of monopiles at the site level and several hundred at the scale of a full wind energy area.

Offshore O&G platforms have functioned as large-scale ecological structures. By introducing hard substrate into predominantly soft-sediment systems, these installations create artificial reefs that rapidly become colonized by diverse biofouling communities (De Mesel et al., 2015; Coolen et al., 2020a). An increase in local biomass and trophic complexity is produced when species like mussels, anemones, bryozoans, crustaceans, and fish congregate around submerged jacket legs and pipelines (Degraer et al., 2020). According to Van Maele et al. (2023), this biodiversity is regarded as a type of "new nature" from an ecological perspective because it would not naturally occur in these sandy environments. As more O&G platforms, as well as aging OWFs, approach end-of-life, the ecological implications of removing such structures have therefore gained increasing attention (Fowler et al., 2018, 2020; Knights et al., 2024).

The presence of artificial hard substrate does more than increase species numbers, it alters local ecological processes (Degraer et al., 2020). Platforms provide refuge and nursery habitat for mobile species such as cod, lobsters, crabs, and various reef-associated fish (Coolen et al., 2020a; Reubens et al., 2010), while biofouling communities filter large volumes of water, modify nutrient flows, and enrich surrounding sediments (Lefaible et al., 2025). Artificial reef communities are also produced by OWFs, and because they contain many more monopiles, these communities are often far larger than those around a single O&G platform. As a result, OWFs can exert a much stronger influence on biodiversity and ecosystem functioning. But, decision-makers must take into account maritime safety, the future use of North Sea space for activities like sand extraction, and the consequences of transforming naturally soft-sediment habitats into hard-substrate systems in addition to habitat loss and ecological function. This larger ecological footprint also influences the debate about their decommissioning. In this broader context, discussions similar to those in the O&G sector are now emerging as the first generation of OWFs approaches the end of its life. Consequently, future OWF policy must come upon a balance between legal requirements, environmental preservation, seabed-use priorities, navigational safety, and increasing public expectations to integrate nature-inclusive design into offshore energy infrastructure.

Therefore, the experience with decommissioning in the O&G sector provides important insights for the future of OWF decommissioning. Decommissioning is more complicated, expensive, and environmentally significant than first thought, as decades of experience have demonstrated. The Brent Spar showed that social expectations, ecological concerns, and transparency are important factors influencing appropriate decommissioning procedures rather than optional extras. Similarly, the disappearance of artificial reef communities surrounding O&G facilities demonstrated that ecological values can build up over time, even on structures that weren't initially intended with the environment in mind. These lessons are valuable for the offshore wind industry, which is distinguished by a significantly higher number of foundations, a heavy reliance on cables and scour protection, and rising expectations regarding circularity and biodiversity. The offshore wind industry can avoid repeating the mistakes of the O&G industry and move toward a more sustainable and socially robust end-of-life strategy by acknowledging the ecological trade-offs, planning realistically for technical and financial uncertainties, incorporating nature-based solutions* and nature-inclusive design* from the outset.

4. Scenarios

Decommissioning OWFs is a complex task involving technical, ecological, legal, and social considerations. As the first generation of OWFs approaches the end of their operational life, there is a growing need to define clear scenarios for removing or partially leaving underwater infrastructure in place. The scenarios combine variations in foundation (monopile), scour protection, and infield cables, which can be removed or retained to varying degrees.

Figure 1 (shown below) visualizes sixteen possible combinations of decommissioning options (Stranddorf et al., 2026). These scenarios are used internationally in research and policy discussions (Spielmann et al., 2023; Stranddorf et al., 2026).

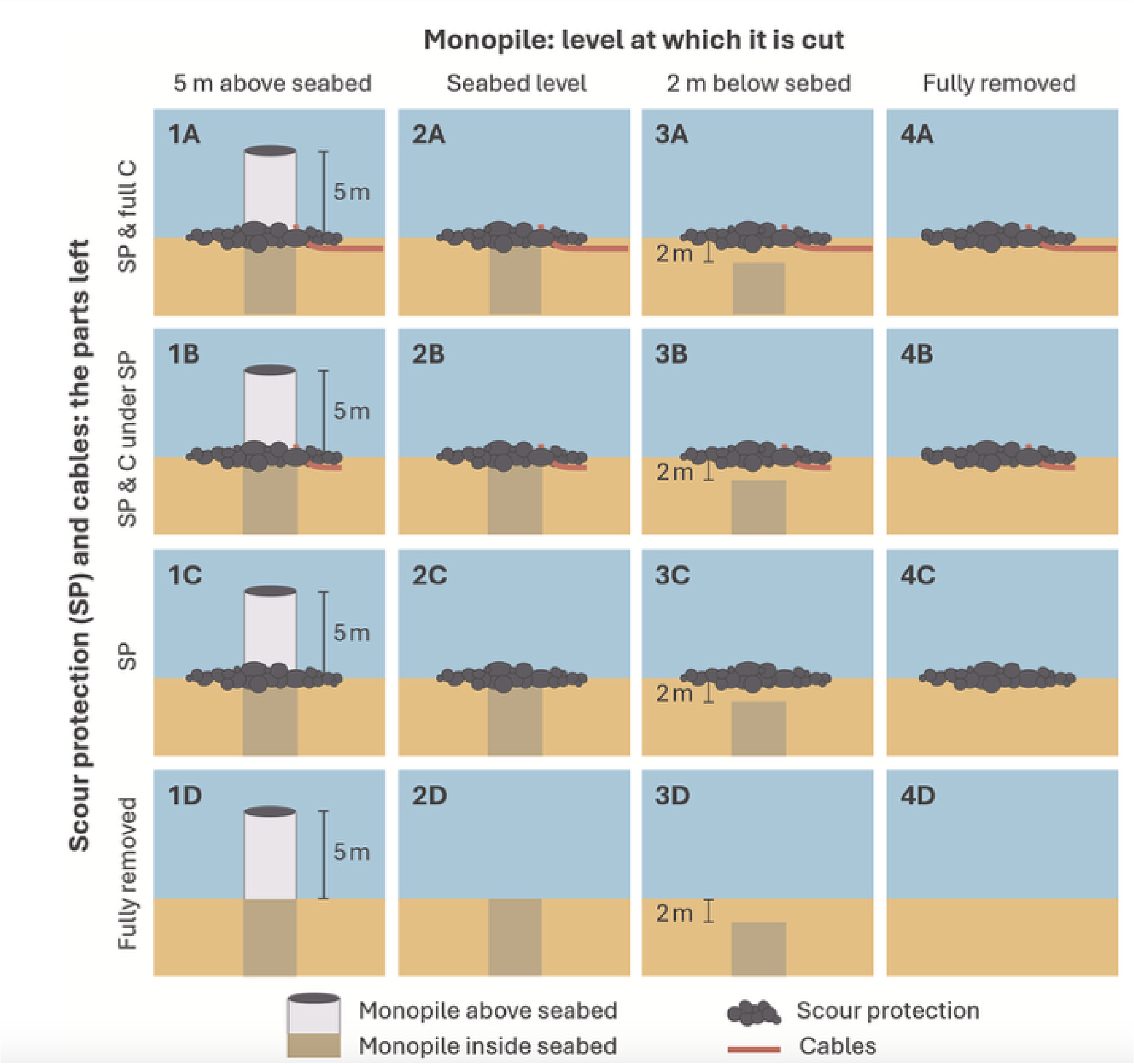

Figure 1: The sixteen decommissioning scenarios studied by Stranddorf et al. (2026) are designated by a combination of a number (1–4) and a letter (A–D). The number indicates which part of the monopile remains after decommissioning, while the letter describes the extent to which scour protection and cables are removed or retained (Stranddorf et al., 2026).

Monopile foundations are the largest and most massive structures of an OWF. They extend dozens of meters into the seabed and account for a significant portion of the total material mass. In practice, four main options for removing monopiles can be distinguished, corresponding to the columns in Figure 1.

The scour protection is usually installed around the monopile to prevent erosion of the seabed and ensure structural stability. The existing scour protection consists of rock with specific size gradations and a layered design, often with filter layers and riprap. As a result, erosion protection forms a complex and durable hard substrate that can be colonized by marine organisms. This structured composition is also relevant from a decommissioning perspective, if the erosion protection were to be removed for reuse, the different rock fractions would have to be recovered and re-sorted, which poses logistical and technical challenges.

Infield cables (inter-array) connect individual wind turbines within the OWF and differ from export cables, which are owned and operated by the transmission system operator (e.g., TenneT in the Netherlands). Infield cables, on the other hand, are owned by the OWF developer. These cables are usually buried under the seabed to reduce the risk of damage. Infield cables are installed at a depth of approximately one meter below the seabed. No mandatory burial depth for infield cables is specified in the Dutch site decisions *(kavelbesluiten).* Installation at approximately one meter below the seabed is therefore primarily a precautionary measure to prevent damage. This differs from export cables, for which burial requirements are explicitly laid down in the licensing framework. In open sea areas, export cables must be buried at a depth of one meter, while in the coastal zone a burial depth of three meters is required.

The various combinations of monopile removal depth, the removal of scour protection, and the removal of infield cables together result in the sixteen decommissioning scenarios illustrated in Figure 1. These scenarios are described below in the various steps.

4.1 Monopile fully removed

Complete removal means that the monopile is completely removed from the seabed. No foundation remains are left behind at the site. The difference between scenarios 4A-4D lies in the treatment of the scour protection and the cables in the field.

Scenario 4A shows that the monopile has been completely removed, but that the scour protection and infield cables remain in place. The seabed is therefore not fully restored to its original sandy state, as hard substrates (scour protection) and buried cables remain in place. Although the entire monopile is removed, this scenario leads to a partial change in seabed conditions.

Scenario 4B also involves the complete removal of the monopile, with the scour protection remaining in place. In this scenario, however, only the cable sections under the erosion protection remain, while the exposed cable sections are removed. This leads to a slightly higher degree of removal compared to 4A, but both the hard substrate and the underground infrastructure remain in place at the site.

Scenario 4C involves the complete removal of the monopile and all cables in the field, while the scour protection remains on the seabed. As a result, no steel foundation elements or cables remain, but the rock revetment continues to function as an artificial hard substrate, preventing full restoration of the original sandy seabed conditions. However, it remains uncertain how this scenario would be practically implemented in real-world decommissioning operations.

Scenario 4D shows the complete removal of the entire structure. This means that the monopile, scour protection and the infield cables are completely removed from the site, so no material is left behind. This scenario restores the site to its original condition (i.e. the state prior to the installation of the wind turbine) and strictly complies with international regulations (OSPAR).

4.2 Monopile 2 m below the seabed

The upper part of the monopile is removed, while the lower part remains in the seabed. Figure 1 shows a removal depth of 2 meters below the seabed (3A-3D). In Dutch practice, however, a greater removal depth of approximately 6 meters is applied. This is due to the dynamic nature of the seabed in the Dutch North Sea, which is characterized by mobile sand waves. These morphodynamic processes can lead to erosion and redistribution of sediment, which means that remains of monopiles that have been cut off at shallow depths can become exposed again over time due to currents and the mobility of the seabed.

Scenario 3A shows a partial removal strategy in which the monopile is cut 2 meters below the seabed, while both the scour protections and the infield cables remain in place.

Scenario 3B also involves cutting the monopile 2 meters below the seabed, leaving the scour protection in place. In this scenario, only the cables below the scour protection remain, while the exposed cables are removed.

Scenario 3C describes a situation in which the monopile is cut 2 meters below the seabed and all infield cables are completely removed, but the scour protection remains at the site.

Scenario 3D represents a more extensive removal approach in which the monopile is cut 2 meters below the seabed. Here, the scour protection and infield cables are completely removed. The only foundation left underground is the buried lower part of the monopile. This largely restores the seabed surface to its original sandy condition. Compared to scenarios 3A-3C, this option minimizes the amount of material left on the seabed surface but does not achieve full restoration due to the remaining buried foundation segment.

4.3 Monopile at seabed level

In these scenarios (2A-2D), the monopile is cut at sea floor level, which means that all vertical foundation elements above the sea floor are removed, while the embedded part of the monopile remains in the subsoil. No foundation material protrudes above the sea floor, but the remaining monopile segment remains permanently buried in the sediment.

Scenario 2A represents a partial removal strategy in which the monopile is cut at sea floor level. In this scenario, the scour protection and infield cables remain in place.

Scenario 2B also involves cutting the monopile at seabed level, with the scour protection remaining in place. In this scenario, only the cables under the erosion protection remain, while the exposed cables are removed. Compared to scenario 2A, this leads to a greater degree of cable removal, but the seabed remains altered by the presence of erosion protection and underground infrastructure.

Scenario 2C describes a situation in which the monopile is cut at sea floor level and all infield cables are completely removed, but the scour protection remains in place.

Scenario 2D describes a more extensive removal option in which the monopile is cut at sea floor level and the scour protection and infield cables are completely removed.

4.4 Monopile 5m above the seabed

In these scenarios (1A-1D), the monopile is partially removed by cutting approximately 5 meters above the seabed, leaving a vertical steel section above the seabed. The embedded part of the monopile remains in the sediment. This option results in a permanent structure above the seabed and represents the least intrusive level of removal of all decommissioning scenarios.

Scenario 1A shows a minimal removal strategy in which the monopile is cut 5 meters above the seabed, leaving both the scour protection and the infield cables in place. This leaves a significant vertical structure standing, surrounded by scour protection, with cables still in place. In this scenario, most of the original offshore infrastructure is retained, and the artificial hard substrate habitat associated with both the monopile and the scour protection is preserved.

Scenario 1B also involves cutting the monopile 5 meters above the seabed, leaving the scour protection in place. In this scenario, only the cables below the erosion protection remain, while the exposed cables are removed.

Scenario 1C also shows a situation in which the monopile is cut 5 meters above the seabed and all infield cables are completely removed, but the scour protection remains in place.

Scenario 1D shows a partial removal strategy in which the monopile is cut off 5 meters above the seabed and the scour protection and infield cables are completely removed. In this case, part of the monopile remains without surrounding scour protection or cables.

4.5 Repowering

Repowering refers to the reuse of an existing OWF site for electricity production by replacing or reusing (part of) the existing infrastructure (Hou et al., 2017). In the context of decommissioning, repowering is an intermediate form between complete removal and permanent termination of use of the site. Repowering can be applied either completely or partially.

In the case of complete repowering, the existing OWF is completely decommissioned, after which a new OWF is built on the same site. All turbines, foundations, cables, and any scour protection are removed (Hou et al., 2017). From the perspective of the decommissioning scenarios, this option is functionally equivalent to complete removal followed by a new installation. There are no direct advantages in terms of material use or environmental impact compared to a new OWF, except for the reuse of the space at sea.

Partial repowering means that certain parts of the existing OWF are retained, while others are replaced. This involves retaining the monopile, transition piece and scour protection, while replacing the tower, nacelle, blades and rotor (Jadali et al., 2021). See Figure 2 for the structure of an offshore wind turbine (Bhattacharya, 2014).

However, the technical feasibility of partial repowering offshore is limited (WindEurope, 2023). Many first-generation OWFs were designed for specific turbine types, loads, and lifespans. Installing a heavier, modern turbine could exceed the original design limits of the foundations, while installing a lighter turbine would reduce energy yield (Stravens et al., 2025). In addition, uncertainties about fatigue, corrosion, seabed dynamics, and long-term stability of scour protection play an important role (Jadali et al., 2021).

Offshore repowering is still rare at present. Forecasts show that repowering will mainly take place on land, while offshore repowering is expected to remain limited to a few specific locations with favorable wind conditions, known soil conditions, and extensive operational data (Stravens et al., 2025). Existing OWFs are often located in good wind locations, which can make repowering attractive from a spatial and energy perspective. As repowering is expected to involve the same activities and impacts similar to those of the installation phase, repowering is considered out of the scope and is not further addressed in this report.

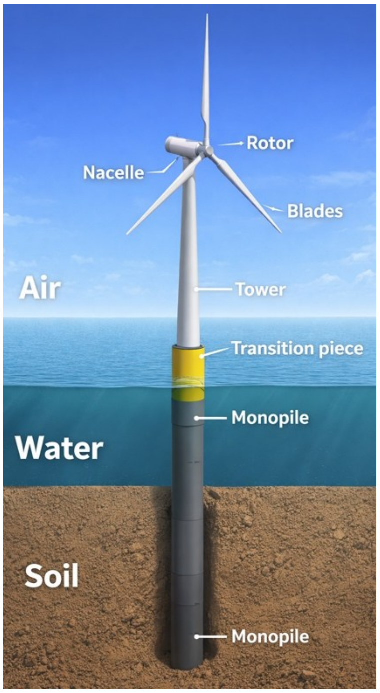

Figure 2: The structure of an offshore wind turbine (Illustrated by Olle Juch, 2026).

4.6 Service life extension

OWFs have an operational lifetime of around 20 to 25 years. However, with proper maintenance, inspection, and monitoring throughout their operational life, this lifespan can be extended to 30 or even 40 years (Adedipe & Shafiee, 2021). In recent years, the average lifespan of OWFs has gradually increased, partly due to improvements in design, materials, and operational strategies. In the Netherlands, this trend is also reflected in policy. For example, the most recent site decisions *(kavelbesluiten)* provide license for a period of 40 years, indicating that a longer operational lifespan is increasingly anticipated in practice.

Service life extension is particularly important financially for OWF operators, as existing installations can generate revenue for longer without the high investment costs associated with repowering or complete decommissioning. In addition, service life extension can contribute to national and European climate targets by producing additional renewable electricity with limited deployment of new infrastructure and associated environmental impacts (WindEurope, 2023).

The original design life of approximately 20 years is often considered the operational lifetime for critical components such as the drive train, generator, and rotor blades. Repairing or replacing these parts can be expensive. So, figuring out which parts are most likely to break is important to keeping inspection and maintenance costs low (Carroll et al., 2016; Shafiee & Sørensen, 2019).

To make life extension economically and technically feasible, a systematic approach to risks is necessary. Failure mode-based risk analyses and evaluations of factors that influence operation and maintenance (O&M) costs are seen as important tools for optimizing life extension strategies (Dinwoodie et al., 2015; Ziegler et al., 2018). Targeted maintenance and condition-based monitoring can limit unplanned outages and excessive costs.

The rapid technological development of inspection and maintenance techniques, such as advanced sensors, digital monitoring, and improved certification schemes, increases the feasibility of service life extension. This allows existing OWFs to remain profitable for longer with relatively limited additional investment (Carroll et al., 2016; Ziegler et al., 2018).

In relation to decommissioning scenarios, service life extension is not a final solution, but a postponement of end-of-life decisions. Service life extension should therefore be considered a temporary strategy within the broader decision-making process on repowering and decommissioning, rather than an alternative that definitively replaces these choices.

5. Techniques

The technical implementation of OWF decommissioning has a significant impact on the feasibility of the various scenarios described in Chapter 4. Although the Dutch legal framework is based on the complete removal of offshore installations, the regulations leave room for different forms of implementation, for example, how the monopiles, scour protection, and cables are removed. This means that the law sets the goal, but not always the means. This is precisely where the need for technical innovation arises.

In recent years, it has become clear that conventional removal techniques are not readily applicable to large-scale OWFs, particularly due to the dimensions of monopiles, the complex structure of scour protection, and the interaction with the seabed. The complete removal of foundations or the recovery of materials from cables and erosion protection poses considerable technical, logistical, and ecological challenges (Topham et al., 2019). As a result, a wide range of innovative techniques are being developed, aimed at more efficient, safer, and less disruptive decommissioning.

In the Netherlands, much of this technological development takes place within research and innovation programs, in which the GROW (Growth through Research, Development & Demonstration in Offshore Wind) consortium plays a central role. Within this consortium, knowledge institutions, contractors, and industry partners are working together on new techniques for decommissioning strategies (GROW, 2025). These innovations are directly linked to the various decommissioning scenarios, such as the complete removal of monopiles (scenarios 4A–4D).

This chapter describes the most important techniques currently being developed and applied for the decommissioning of OWFs. A distinction is made between techniques for complete and partial removal of monopiles, methods for dealing with scour protection, and techniques for removing cables.

5.1 Monopiles complete removal

One of GROW's projects involves developing a hydraulic extraction method for removing monopiles. Interviews with technical experts indicated that the approach of cutting monopiles below the seabed leaves large volumes of steel in situ, which is unacceptable from a safety and policy perspective. Residual structures may re-exposed due to seabed dynamics and pose risks to shipping anchoring and bottom trawling fisheries. In the HyPE-ST project (Hydraulic Pile Extraction Scale Tests), researchers investigated a technique based on hydraulic extraction. In this method, after removing the upper structure of the wind turbine, the pile is sealed, the cavity is filled with water and pressurized, causing the pile to be pushed upwards (GROW, 2025). This hydraulic extraction approach corresponds to scenario 4D in Table 1, in which the monopile is completely removed rather than cut and partially left in situ.

The technique has now been tested on a medium scale in Germany, following successful small-scale trials in the Netherlands. The test setup simulated piles with a diameter of 1.5 meters, with extraction taking approximately 20 to 30 minutes. However, a major challenge is how existing monopiles, which do not have a perfectly flat sealable top, can be effectively sealed in the field. Cable penetrations and inspection openings must also be sealed before pressure can be built up. The project is also working on numerical models that predict the required breakout pressure under different soil conditions.

In addition to hydraulic extraction, other techniques are also being investigated. For example, a method is developed that uses vibration to loosen monopiles. Moreover, another technique is being developed that combines jetting and rotary movement to soften the surrounding soil. The focus here is on soil softening, the pile is temporarily placed in a liquid state of the soil, as it were, because the grain stresses disappear. The forces between the grains then become virtually zero and the soil behaves like a liquid. Such techniques are typically developed by contractors in collaboration with independent research institutes (e.g. Deltares) for scale testing and model development.

Furthermore, there is growing interest in recovering materials from monopiles, particularly steel. From the perspective of circularity and raw material, complete removal is therefore attractive, provided that the ecological and technical impact remains manageable.

Recent simulation-based cost assessments for a representative 2 GW Dutch OWF indicate that a full monopile extraction campaign is expected to take approximately 132.9 days, including weather-related delays (Mancini, 2026). This duration reflects a single continuous campaign using a heavy lift vessel and vibro-extraction technology under average North Sea metocean conditions. It should be noted that actual project durations may vary depending on soil conditions, port distance, vessel availability and seasonal weather variability (Mancini, 2026).

5.2 Monopiles partial removal

In partial monopile removal, the foundation is not completely extracted from the seabed, but cut at a predetermined height or depth, leaving part of the monopile in situ. This approach is illustrated in Figure 2 from the studies by Spielmann et al. (2023) and Stranddorf et al. (2026), which describe several decommissioning scenarios and represent a technically distinct alternative to complete removal. The technique used and its technical feasibility are closely related to the chosen cutting depth, as shown in the various scenarios in Table 1.

Cutting instruments encompass flame cutting, wire cutting, abrasive water jet cutting, cutting using linear shaped charges (explosives), blade sawing, and laser cutting. Although explosives can be handled safely with respect to worker health, they are commonly dismissed as an option primarily due to environmental concerns (Gjødvad & Ibsen, 2016).

In *scenario 1D*, the monopile is cut approximately five meters above the seabed. This scenario can be technically implemented using relatively simple mechanical cutting or sawing techniques, as the cut is above the sediment and direct access is possible. The technical complexity is limited, and the implementation risks are relatively low. On the other hand, a significant portion of the steel monopile remains above the seabed, which can be considered undesirable from a policy and safety perspective. Moreover, standing foundation structure may conflict with other uses of the sea, such as shipping and fishing.

Scenario 2D involves cutting the monopile at the seabed level. In this case, the transition zone between water and sediment is cut, which places higher demands on positioning and stability during execution. Both mechanical cutting techniques and internal cutting techniques can be applied here, but the interaction with the surrounding sediment increases the technical uncertainty compared to scenario 1D.

In *scenario 3D,* the monopile is cut approximately two meters below the seabed. Mechanical cutting techniques are generally not suitable for this cutting depth, and cutting techniques such as abrasive water jet cutting, performed from the inside of the monopile, are used. This requires the sediment to be removed from the monopile first, for example, by flushing or airlifting. Although this technique enables precise cutting below the seabed, its application in large-scale offshore wind foundations has not yet been tested to a limited extent. Consequently, scenario 3D has a higher degree of technical complexity and uncertainty than the shallower cutting scenarios.

In summary, the scenarios in Table 1 show that cutting and shearing techniques mainly determine the feasibility of partial removal of monopiles (scenario 1D–3D).

Table 1: Overview of monopile cutting and removal techniques per scenario (1D–4D).

Scenario	Monopile approach	Cutting depth relative to seabed	Primary technique applied	Technical complexity	Key uncertainties
1D	Partial removal	~5 m above the seabed	Mechanical cutting or sawing techniques	Low	Structural stability of the remaining steel section, risk of damage during cutting, ecological and policy acceptance of a remaining vertical steel structure.
2D	Partial removal	At seabed level	Mechanical sawing or internal cutting techniques	Medium	Accurate positioning of the cut at seabed level, stability of the monopile during cutting, interaction with surrounding sediments.
3D	Partial removal	~2 m below the seabed	Abrasive water jet cutting (internal cut)	Medium - high	Removal of sediment from inside the monopile, cutting reliability for

					large-diameter piles, limited large-scale operational experience.
4D	Complete removal	n.a. (monopile fully extracted)	Hydraulic extraction or vibration/jetting-based techniques (possible cutting as a preparatory step)	Medium - high	Effective sealing of the monopile, required extraction forces under different soil conditions, scalability to modern large diameter monopiles, limited large-scale operational experience.

In the case of partial removal (cutting at 6 m below seabed), the expected campaign duration increases substantially to approximately 236.9 days for a 2 GW reference OWF, including weather-induced delays (Mancini, 2026). The longer duration is primarily driven by internal dredging, cutting operations, and feeder logistics, which introduce additional weather sensitivity and operational complexity compared to full extraction in sandy soils (Mancini, 2026).

5.3 Scour protection

Scour protection keeps the seabed from eroding and guarantees the stability of a wind turbines foundation for the duration of its operation. As mentioned earlier in Chapter 4, scour protection consists of multiple layers of stone with specific gradations and a layered structure.

Technically speaking, scour protection can be removed, but specialized offshore operations are needed. According to contractor interviews, if removed, this is currently done using either large vessels equipped with heavy lifting equipment or traditional dredging vessels. Due to the large volumes and weights involved, removal is typically described as technically demanding, and there has not been much innovation in these techniques up to this point.

The intended destination and reuse pathway have a significant impact on how the scour protection is handled after removal. An important distinction must be made between offshore storage and transport to shore for further processing.

When the scour protection is brought onshore, it is necessary to rinse the material to remove attached marine organisms, sediment, and organic material. This rinsing is required to prevent the spread of non-native species, comply with biosecurity and waste regulations, and to make the material suitable for further processing. After rinsing, the scour protection is sorted by size, for example, for disposal or possible reuse, such as in new scour protection systems or other coastal and hydraulic engineering applications.

Rinsing scour protection offshore is complex in practice and is also restricted by environmental regulations. Offshore rinsing results in the direct discharge of organic material, sediment, and potentially contaminated rinse water into the marine environment, which can conflict with permit requirements and water quality standards. For this reason, active rinsing offshore is avoided, any cleaning occurs passively at most through natural hydrodynamic processes during lifting and transport. Onshore rinsing, on the other hand, can take place in a controlled environment, where the rinse water and released materials can be collected, treated, and disposed of in accordance with applicable environmental and waste regulations. This makes onshore processing generally the preferred option when scour protection is intended for reuse or long-term storage, despite the additional logistical effort involved.

Overall, the removal of scour protection involves a sequence of technically intensive steps, from offshore recovery to transport, processing, and potential reuse or disposal. These technical considerations play a key role in determining whether removal is pursued in specific decommissioning scenarios and form an important basis for evaluating the associated ecological effects in subsequent chapters.

Scour protection removal is the longest single campaign component, with an expected duration of approximately 348.9 days for a 2 GW reference OWF, including weather-induced delays (Mancini, 2026). The extended duration is mainly caused by the relatively low net productivity of grab dredgers in offshore conditions and the strong sensitivity of seabed rock removal operations to weather constraints (Mancini, 2026).

5.4 Cables

In addition to monopiles and scour protection, cables are an important but often overlooked part of OWFs during decommissioning. Within an OWF, this mainly concerns the inter-array cables that connect the turbines to each other and transport the electricity to the offshore substation platform. These cables are usually buried in the seabed. The inter-array cables located in the OWF itself are owned by the OWF owner and are therefore fully covered by the OWF's decommissioning plan. Export cables are the responsibility of TenneT in the Netherlands.

Removing cables presents specific technical challenges, partly because cables are not uniformly located in or on the seabed. Due to seabed dynamics, such as sand waves and sediment transport influenced by tidal and bottom currents, the local sediment structure around cables can change over time. This can cause cables to gradually become covered with additional sediment or, conversely, become (partially) exposed, without the cable itself being actively moved. This dynamic occurs not only along export routes but also within OWFs where infield cables are located (Spielmann et al., 2023).

When cables are relatively shallow or have been (partially) washed free, removal can be relatively simple. In practice, this means that the cable can be removed using light excavators, grabs, or cable-pulling systems and then pulled out of the sediment in a controlled manner. However, for deeper-buried cables, this is considerably more complex. In such cases, jetting techniques are required, in which high-pressure water is injected to loosen the sediment around the cable, or specialized mechanical pullers that gradually lift the cable from the ground.

In addition, traditional removal techniques, such as mechanical excavation or the use of water jets, can lead to significant disturbance of the seabed and increased water turbidity. These effects are exacerbated by natural sediment dynamics and local compaction of the soil.

Furthermore, there is growing interest in recovering materials from cables, particularly copper and aluminum. From a circularity and raw material perspective, complete removal is therefore attractive, provided that the ecological and technical impact remains manageable.

A recently developed technique for removing cables uses controlled vibrations to locally weaken the sediment above and around the cable. This method, uses a specialized device that functions similarly to a reverse trencher. By temporarily loosening the sediment without large-scale excavation, the seabed's resistance is reduced, allowing the cable to be removed with significantly lower tensile forces. This reduces the risk of cable breakage and minimizes seabed disturbance. The technique is currently in the research and demonstration phase but is considered promising for future large-scale decommissioning applications (Frequensea, 2025).

The removal of inter-array cables is estimated to require approximately 251.9 days for a 2 GW reference OWF, including weather-induced delays (Mancini, 2026). Although individual cable sections can be removed relatively efficiently, the large total cable length and frequent port transits significantly extend the overall campaign duration (Mancini, 2026).

6. Birds & Bats

After discussing the technical decommissioning scenarios, this chapter shifts its focus to the ecological impacts on birds and bats. The upcoming chapters (6 – 9) focuses on the implications for species using the OWF area during and after the decommissioning phase. Birds and bats may be exposed to disturbance during this phase due to increased shipping, underwater and above-ground activities, artificial lighting, and the (temporary) loss or change of habitat. This chapter addresses the specific disturbances and risks expected for birds and bats during the decommissioning phase, and the extent to which these effects differ in nature and magnitude from the ecological impacts known from the construction and operational phases of OWFs.

6.1 Ecological effects

For birds and bats, the ecological effects during decommissioning are mainly determined by temporary disturbances, changes in habitat structure, and adjustments in collision and disorientation risks. Decommissioning can cause locally and temporarily relevant ecological effects, particularly when work coincides with migration, moulting, or peak foraging periods (Fortune & Paterson, 2020; Ronconi et al., 2015).

Significant sources of disturbance during decommissioning include an increase in shipping movements, elevated noise levels above water, and intensive (work) artificial lighting, including nighttime lighting on work vessels (Ronconi et al., 2015; Walsh et al., 2024). In addition, the removal of turbines and associated structures leads to a fundamental change in the spatial configuration of the area, transforming an infrastructure-dominated marine landscape back into open sea. This transition can have both positive and negative effects, depending on species-specific sensitivities and the use of the OWF during the operational phase (Fortune & Paterson, 2020).

Compared to the construction phase, decommissioning does not involve pile driving, and underwater noise levels are therefore generally lower (Fortune & Paterson, 2020). However, above-water disturbance, visual presence of vessels, and lighting intensity may be comparable to, or locally exceed, those observed during construction, particularly when activities are concentrated in a short period (Ronconi et al., 2015; Walsh et al., 2024).

Compared to the operational phase, long-term structural risks such as turbine collision are largely eliminated, while temporary disturbance and disorientation risks may increase due to intensified and less predictable human activity, especially under adverse weather or low-visibility conditions (Ronconi et al., 2015).

6.1.1 Seabirds and shorebirds

Disturbance and displacement effects
During decommissioning, human activity within the OWF will temporarily increase. Additional shipping, crane activities, above-water noise, and artificial lighting may disturb the resting, foraging, and migration areas of marine and coastal birds (Fortune & Paterson, 2020; Walsh et al., 2024).

Species particularly sensitive to shipping disturbance include divers (e.g., red-throated diver, *Gavia stellata*), sea ducks such as common eider (*Somateria mollissima*), and auks, including common guillemot (*Uria aalge*) and razorbill (*Alca torda*) (Soudijn et al., 2025). These species may be temporarily displaced from the area. These effects are usually local and on short-term, but can become ecologically relevant if the work takes place during winter periods, peaks in seasons or when cumulative effects occur, for example if multiple OWFs are decommissioned simultaneously or if decommissioning overlaps in time with other offshore activities (Ronconi et al., 2015).

Habitat change
Removing OWFs results in the restoration of open sea conditions and the disappearance of vertical infrastructure. For bird species that avoid OWFs during the operational phase, this can lead to a reduction in functional habitat loss and barrier effects. In particular, species that are sensitive to the moving structures or rotational movements can once again make use of the area. In this sense, decommissioning can have a positive ecological effect for these species groups, as previously avoided habitat becomes available again (Fortune & Paterson, 2020).

At the same time, the disappearance of hard structures can have negative effects on species that use the OWF functionally, for example as a resting place, lookout point, or foraging area. Studies on offshore platforms shows that gulls (e.g., herring gull, *Larus argentatus*), cormorants (e.g., great cormorant, *Phalacrocorax carbo*) and other generalist species may exploit man-made structures as resting or feeding sites, particularly during migration or poor weather conditions (Ronconi et al., 2015). Decommissioning can result in a loss of functional habitat for these species locally.

Research into habitat loss among seabirds shows that the ecological effects of OWFs largely arise from functional habitat loss as a result of avoidance behavior, rather than physical destruction of habitat. Various seabird species avoid OWFs and areas with increased human activity, effectively reducing the availability of suitable foraging and resting areas (van Kooten et al., 2019). This process is particularly relevant during the operational phase, when OWFs are present for long periods of time and avoidance can occur on a structural basis.

During the decommissioning phase, the way in which habitat loss or disturbance arises changes fundamentally. On the one side, human activity temporarily increases, partly due to additional shipping and work activities, which can lead to short-term disturbance and temporary displacement of disturbance-sensitive species (Fortune & Paterson, 2020). Previous research shows that the regular presence of ships, such as maintenance vessels, can be sufficient to drive sensitive species, such as red-throated divers (*Gavia stellata*), out of an area (van Kooten et al., 2019). In this sense, the decommissioning phase is similar to the construction phase, but on a smaller temporal scale.

Although, removing turbines and associated infrastructure eliminates the structural cause of habitat loss. For species that avoid OWFs, this can result in the re-availability of suitable habitat. Decommissioning thus constitutes a transitional phase from long-term functional habitat loss to potential habitat restoration, whereby temporary disruption gives way to a structural improvement in the spatial suitability of the area (Fortune & Paterson, 2020).

Population models show that the effects of habitat loss during the operational phase can accumulate over several decades and could potentially result in population level effects. However, these outcomes are strongly dependent on model assumptions regarding spatial overlap and species specific sensitivity (van Kooten et al., 2019; Soudijn et al., 2025). The decommissioning phase differs in that the effects are temporary, local, and in principle reversible. Although disturbance during decommissioning can be ecologically relevant when it coincides with moulting or migration peaks, the expected effect size is smaller than that of the operational phase, in which habitat loss is continuous.

This means that during decommissioning, the dominant effect shifts from chronic habitat loss to acute but short-term disturbance, while at the same time the preconditions are created for the recovery of open sea habitat. However, the extent to which seabirds will actually reuse this regained area, and the speed at which this will happen, remain an important knowledge gap.

Collision risk and disorientation

The risk of collision with rotor blades decreases significantly during decommissioning because turbines are taken out of service or removed. This means that the risk is considerably lower than during the operational phase. However, temporary lighting on ships and platforms may, in exceptional cases, cause disorientation of nocturnal migratory birds and migrating bats, especially in poor weather conditions. However, this risk is considered limited in the EIA and is highly dependent on the duration and intensity of nighttime activities.

Comparison with construction/operational phase

Compared to the construction phase, the physical disturbance is generally less prolonged, while the spatial scale of disturbance may be comparable. Compared to the operational phase, the effect shifts from a chronic, long-term presence of structures to a temporary but intensive disturbance. The ecological significance of this shift depends heavily on the timing, duration, and location of the decommissioning activities.

6.1.2 Migratory birds

The North Sea is an important migration area for migratory birds, with both daytime and nighttime migration taking place. During decommissioning, increased light levels and additional shipping traffic may cause temporary disruption or disorientation, particularly during nighttime migration (Walsh et al., 2024). Unlike during the operational phase, when turbines pose a potential structural barrier and collision risk, this risk is more limited during decommissioning. The ecological impact on migratory birds is therefore mainly determined by the extent to which activities overlap with migration peaks and by the intensity of nighttime activities.

6.1.3 Bats

For bats, the knowledge base in the offshore environment is still very limited. Although increasing research shows that migrating bats cross the North Sea (Hooker et al., 2025), their behavior around OWFs is still not sufficiently understood. Bats can die at OWFs as a result of direct collision with the moving rotor blades (known as blunt-force trauma), or due to barotrauma. Barotrauma refers to internal tissue damage, particularly to the lungs and hearing organs, caused by rapid changes in air pressure in the vicinity of the rotor blades (Baerwald et al., 2008; Grodsky et al., 2011). During the decommissioning phase, no direct collision risks with rotor blades are expected, as turbines will be shut down or removed. Potential effects are limited to indirect disturbance from lighting and shipping (Walsh et al., 2024). Artificial lighting can have both an attractive and an aversive effect, depending on the species and context. Some hypotheses suggest that light attracts insects, which in turn may attract bats (Guest et al., 2022), while other studies point to avoidance behavior (Walsh et al., 2024). For decommissioning, there is a lack of evidence to quantify these mechanisms. Interviews with stakeholders confirm that for bats at sea, "virtually all knowledge is lacking," leaving the direction and extent of the effect uncertain.

Compared to the operational phase, in which collisions and barotrauma are possible causes of mortality, decommissioning appears to be less ecologically risky for bats. Nevertheless, the evidence is weak, and caution is still advised when planning nighttime operations.

6.2 Mitigation measures

A key mitigating principle during the decommissioning phase is avoiding ecologically sensitive periods, such as peak migration, molting, or intense foraging. Scheduling activities outside these periods can significantly reduce the risk of ecologically significant disturbance.

Furthermore, limiting the intensity and duration of disturbance is important. This can be achieved, for example, by clustering activities over time, avoiding simultaneous disturbance-intensive activities, and optimizing logistics and shipping routes to prevent unnecessary shipping movements.

6.2.1 Birds

For birds, mitigation focuses on limiting disturbance from shipping, overwater noise, and lighting. Scheduling work outside periods with high bird concentrations, such as wintering periods, moulting periods, and peak migration periods, is one of the most effective measures to limit temporary disturbance and displacement.

Reducing disturbance from shipping can be achieved by minimizing vessel movements, using fixed shipping routes, and restricting vessel speeds in ecologically sensitive areas.

Artificial lighting poses a specific risk factor, particularly for night migrating birds. Mitigation can consist of using targeted, shielded, and low-intensity lighting, avoiding unnecessary lighting and limiting the use of continuous, bright lighting. Where possible, lighting can be temporarily switched off or dimmed during peak night migration periods, particularly in poor visibility or low cloud cover.

Regarding habitat change, the method of decommissioning can influence ecological impacts. In specific cases, the (partial) removal of OWFs, such as scour protection, can contribute to the preservation of benthic communities and thus indirectly to the availability of food for higher trophic levels, including fish and seabirds. However, such choices require a careful balance between ecological benefits and policy or safety criteria.

6.2.2 Bats

The data of bats in the offshore environment is very limited, which is why mitigation during the decommissioning phase is primarily based on the precautionary principle. Because known risks during the operational phase, such as collisions and barotrauma, largely disappear during the decommissioning phase, mitigation focuses primarily on limiting indirect disturbance.

A key measure is limiting nighttime work and lighting, particularly during known migration periods. The use of targeted, warm-colored, and low-intensity lighting can help reduce attracting or disruptive effects. Where nighttime work is unavoidable, limiting the duration and spatial extent of illuminated areas can contribute to risk reduction.

Given the significant uncertainties surrounding bat behavior at sea, it is advisable to be cautious about assuming the absence of risks when planning decommissioning activities. Combining mitigation with targeted monitoring can contribute to an adaptive approach, where measures can be adjusted based on new insights.

6.3 Knowledge gaps

6.3.1 Birds

A significant knowledge gap concerns the speed and extent to which bird communities adapt to the disappearance of OWF infrastructure. During the operational phase, there is habitat change and possible habitat loss or gain, depending on the species. Since OWFs are typically present for several years, up to about 40 years, this period can span several generations of birds, potentially leading to long-term adaptations in behaviour or at the population level. After decommissioning, open sea is restored, but it is unknown how quickly birds will recolonize this space and to what extent previous avoidance will be lifted. The temporal dynamics of this recolonization represent an important knowledge gap.

6.3.2 Bats

For bats, the knowledge gap is even greater than the expected direction of impact. Data on presence, behavior, and sensitivity to disturbance at sea are scarce, and virtually nonexistent for the decommissioning phase. Essential questions concern migration routes, phenology, flight altitudes, and reactions to light and shipping (Hooker et al., 2025). Without targeted monitoring, it remains impossible to make robust statements about effects and to develop proportionate mitigation measures. Longterm and systematic monitoring is therefore necessary to fill these knowledge gaps.

7. Marine Mammals

This chapter takes a closer look at the potential ecological effects of the decommissioning phase of OWFs on marine mammals. The analysis focuses on harbour porpoises *(Phocoena phocoena)*, harbour seals *(Phoca vitulina)*, and grey seals *(Halichoerus grypus)*, which are among the most common marine mammal species in the Dutch North Sea (Common Wadden Sea Secretariat, 2022). This chapter addresses how underwater noise and vibrations generated during decommissioning of OWFs may affect harbour porpoises and seals, and how severe and long-lasting these effects are in comparison to those observed during the construction phase. Marine mammals rely heavily on acoustic stimuli for essential life functions such as communication, navigation, predator avoidance, and foraging, making them especially vulnerable to changes in the underwater soundscape. Underwater noise is therefore considered a key stressor for this species group. By comparing the nature, intensity, and duration of noise exposure during decommissioning with those associated with the construction phase, this chapter aims to provide insight into the relative ecological significance of decommissioning related disturbances for marine mammals.

Underwater noise in the marine environment originates from both natural and anthropogenic sources, with human activities increasingly dominating the soundscape of the North Sea. Major anthropogenic sources of underwater noise include commercial shipping, offshore construction activities such as pile driving, dredging, and seismic surveys, as well as operational activities at offshore installations (Hildebrand, 2009; Richardson et al., 1995). Pile driving during the construction phase of OWFs is considered one of the most significant sources of impulsive underwater noise, next to exploding UXO's (military munitions), characterized by short, high-intensity sound pulses that can propagate over large distances and cause behavioral disturbance, temporary threshold shifts, or displacement of marine mammals (Madsen et al., 2006; Southall et al., 2007; Tougaard et al., 2009). In contrast, the decommissioning phase does not involve pile driving, and therefore impulsive noise is largely absent. Instead, decommissioning activities mainly generate continuous or semi-continuous noise from operations such as the removal of scour protection by stone grabbing, cutting or lifting of foundations, hydraulic pile extraction for loosening structures, and the extraction of export and inter-array cables (Dannheim et al., 2020; Heinis et al., 2015). These activities are expected to produce lower sound pressure levels compared to construction-related piling, but over longer durations. As a result, marine mammals are more likely to be exposed to prolonged continuous noise rather than short-term impulsive noise during decommissioning, potentially leading to different types of behavioral responses and stress effects.

7.1 Ecological effects

The ecological impacts of decommissioning OWFs on marine mammals are strongly related to the production of underwater noise and vibrations. In the Dutch part of the North Sea, the harbour porpoise *(Phocoena phocoena),* the harbour seal *(Phoca vitulina)*, and the grey seal *(Halichoerus grypus)* are among the most common marine mammals. However, these species groups differ significantly in ecology, hearing sensitivity, and behavior, resulting in significant differences in their sensitivity to noise. For this reason, the impacts on porpoises and seals are discussed separately below.

7.1.1 Porpoises

The harbour porpoise is the most common cetacean in the North Sea, occurring in both coastal and offshore areas (Hammond et al., 2013; Reid et al., 2003). Harbour porpoises rely heavily on acoustic signals for echolocation, navigation, and foraging. They use very high frequencies, with optimal hearing sensitivity around 100–150 kHz, making them particularly sensitive to disturbances in the acoustic environment (Kastelein et al., 2002; Southall et al., 2007). Compared to seals, harbour porpoises are therefore generally more sensitive to changes in the underwater acoustic environment, especially when these disturbances occur in important foraging or breeding areas.

During the construction phase of OWFs, pile driving has been shown to lead to large-scale, temporary habitat avoidance by harbour porpoises and to significant decreases in local densities (Brandt et al., 2011; Tougaard et al., 2009). It has also been suggested that intense noise sources during calving can disrupt the mother-calf relationship, with calves potentially losing their mothers due to panic reactions or spatial separation (Dähne et al., 2013).

However, during the decommissioning phase, such impulsive noise sources as pile driving are not used. The expected noise production consists mainly of continuous or semi-continuous sources, such as removing scour protection, cutting or lifting foundations, and pulling out cables (Heinis et al., 2015). These activities generally produce lower noise levels than pile driving but can occur over longer periods. For harbor porpoises, this means that the effects are expected to be limited to temporary behavioral changes, such as avoidance of the immediate work area or interruption of foraging (Southall et al., 2007; Heinis et al., 2015).

7.1.2 Seals

The common seal and the grey seal are widespread in the Dutch North Sea and use both shallow coastal zones and offshore foraging areas (Brasseur et al., 2015). Unlike harbor porpoises, seals are less dependent on acoustic signals for foraging and have a hearing sensitivity primarily at lower frequencies, roughly between 1 and 50 kHz (Kastelein et al., 2009). Consequently, seals are generally less sensitive to underwater noise than harbor porpoises.

Telemetry studies have shown that operational OWFs pose no clear physical or functional barriers to seals. Both common and grey seals regularly pass OWFs and do not show consistent avoidance (McConnell et al., 2012). In fact, several studies suggest that seals actively use offshore structures as foraging areas, possibly due to increased food availability around foundations (Russell et al., 2014).

During the decommissioning phase, seals are expected to experience primarily temporary disturbances in the form of avoidance behavior, disruption of resting or foraging activities, and temporary retreat from the immediate work area. These effects fall under the broader concept of anthropogenic disturbance and are generally considered local and temporary (Brandt et al., 2013). The use of Acoustic Deterrent Devices (ADDs) can increase the disturbance distance. However, based on current knowledge and expected decommissioning practices, such devices are likely to be used less frequently and less intensively during decommissioning than during the construction phase.

The risk of hearing damage to seals during the decommissioning phase is estimated to be low. Activities such as cutting or lifting structures and removing scour protection may contain impulsive sound components, but these are considerably less intense than impact piling. Vibratory techniques and hydraulic extraction of piles primarily produce low-frequency and relatively weak sound, making TTS or PTS unlikely (Heinis et al., 2015; Southall et al., 2007).

7.1.3 Comparison with construction phase

Compared to the construction phase, the ecological impacts of underwater noise during the decommissioning phase are generally less extreme. This difference is primarily explained by the absence of longterm, repeated impulsive noise sources such as pile driving, which are responsible for large-scale habitat avoidance and disturbance of marine mammals during the construction phase (Brandt et al., 2011; Tougaard et al., 2009). Decommissioning activities are typically shorter, spatially more limited, and have lower noise levels (Heinis et al., 2015), assuming that non-explosive cutting techniques are used. The use of explosives would generate high-intensity impulsive noise and could lead to disturbance levels more comparable to construction activities. Although temporary disturbances can also occur during the decommissioning phase, the available literature indicates that these effects are local, temporary, and reversible, with no evidence of population-level effects (Brandt et al., 2011; Heinis et al., 2015; Tougaard et al., 2009).

7.2 Mitigation measures

Although the ecological impacts of underwater noise during the decommissioning phase of OWFs are generally less extreme than during the construction phase, mitigation measures remain necessary to limit temporary disturbance to marine mammals. During decommissioning, activities such as removing foundations, removing scour protection, and pulling out cables can lead to increased noise levels, which can cause behavioral changes, particularly in harbor porpoises and seals (Heinis et al., 2015; Brandt et al., 2013). Because these effects are primarily temporary and behavioral, mitigation focuses primarily on limiting exposure in time and space, rather than preventing physical hearing damage.

A key principle of mitigation during the decommissioning phase is the principle of proportionality. This means that the nature and intensity of the mitigating measures must be in proportion to the expected scale, duration, and severity of the impacts (Heinis et al., 2015). While measures may be necessary during the construction phase to prevent hearing damage, during decommissioning, the focus is primarily on limiting temporary behavioral disruption, for example, by carrying out work outside ecologically sensitive periods or by limiting the duration of exposure.

Mitigation measures may involve temporal planning of activities so that decommissioning occurs outside ecologically sensitive periods for marine mammals, including calving or peak presence periods, to minimize the risk of disturbance.

7.2.1 Porpoises

Harbor porpoises are particularly sensitive to disturbances in the underwater acoustic environment due to their strong reliance on echolocation for orientation and foraging. Mitigation measures for this species therefore, primarily focus on preventing disturbance during ecologically sensitive periods, such as calving, lactation and seasons with low prey availability (Brandt et al., 2011; Dähne et al., 2013).

In permitting procedures for offshore activities in the Dutch North Sea, the period from the first of May to the first of September is often designated as a vulnerable period for reproduction. Scheduling noise-intensive decommissioning activities outside this period can reduce the risk of disrupting mother-calf relationships. Although no direct studies are available demonstrating the effects of decommissioning on mother-calf relationships, it is likely that sudden increases in noise during the decommissioning phase can also lead to temporary separation, but to a lesser extent than with impact piling (Southall et al., 2007).

In addition, establishing a temporary precautionary zone around the work zone can contribute to risk reduction. This is not a permanent noise-free zone, but an operational safety zone where harbor porpoises are monitored for their presence prior to any noise-producing activities. If animals are observed within this zone, the start of work can be postponed. This principle is supported by studies of harbor porpoise behavioral responses to impulsive noise sources, where avoidance occurs on a scale of several kilometers, depending on the source and noise level (Tougaard et al., 2009; Brandt et al., 2011).

The use of acoustic deterrent devices (ADDs) for harbor porpoises is used with caution. Although ADDs can be effective in temporarily keeping animals at bay, they themselves cause disturbance and can lead to temporary habitat avoidance (Brandt et al., 2013). Therefore, a combination of limited use of ADDs and real-time monitoring, for example via Passive Acoustic Monitoring (PAM), is increasingly being chosen to determine the presence of harbour porpoises in the vicinity of work activities (JNCC, 2017).

7.2.2 Seals

Seals are generally less sensitive to underwater noise than harbor porpoises and more often exhibit habituation to temporary disturbances. Nevertheless, noise-producing activities during decommissioning can lead to temporary disruption of resting and foraging behavior, especially when work takes place near important resting or feeding sites (Brasseur et al., 2015).

For seals, mitigation focuses primarily on avoiding disturbance during the breeding and nursing periods. In Dutch permitting practice, species-specific vulnerable periods are defined for this purpose. For the harbor seal, this period generally runs from May until mid-August, while for the grey seal, it typically spans from mid-November until the end of December (Aramis, 2025). Scheduling decommissioning activities outside these periods reduces the risk of disturbing pups and lactating females.

The use of ADDs may be more effective for seals than for harbor porpoises, as seals are more sensitive to lower frequencies and react more quickly to deterrent sounds. However, ADDs should also be used only temporarily and preferably combined with monitoring to prevent unnecessary disturbance on a larger scale (Southall et al., 2007; Brandt et al., 2013).

Furthermore, source control measures, such as implementing quieter working methods, limiting working hours, and avoiding simultaneous noise-intensive activities, can contribute to reducing the total noise impact. Such measures are particularly effective during the decommissioning phase, as work is short-term and project-specific (Heinis et al., 2015).

7.3 Knowledge gaps

Despite increasing attention to the ecological effects of OWFs, considerable uncertainty remains regarding the specific effects of the decommissioning phase on marine mammals. Most of the available knowledge is based on studies of the construction phase, particularly impact piling, while data on noise levels, noise characteristics, and biological responses during the decommissioning phase are scarce. This makes it difficult to determine impact distances, exposure thresholds, and recovery processes with the same degree of certainty as for the construction phase.

A significant knowledge gap concerns the lack of field measurements during actual decommissioning projects. Current insights are largely derived from studies of comparable offshore activities, such as geotechnical drilling, cutting, and vibration-related techniques. While these studies provide valuable indications of potential noise levels and behavioral responses, the extent to which these results are directly applicable to decommissioning is uncertain. Variations in techniques used, duration of the work, and local environmental conditions can lead to divergent noise profiles and ecological effects.

Furthermore, there is limited knowledge about the cumulative effects of decommissioning in combination with other human activities at sea, such as shipping, maintenance work on nearby OWFs, and the simultaneous decommissioning of OWFs. Little is also known about delayed effects, such as changes in energy balance, foraging efficiency, or reproductive success, which are not directly visible in short-term behavioral studies but are important for impact assessment and mitigation strategies.

7.3.1 Porpoises

For harbor porpoises, a specific knowledge gap exists regarding the effects of continuous and semi-continuous noise sources during the decommissioning phase. While the effects of impulsive noise on harbor porpoises are relatively well documented, less is known about the extent to which longer, less intense noise leads to subtle behavioral changes, such as reduced foraging efficiency or increased energetic costs.

Furthermore, knowledge is lacking regarding the effects of decommissioning during ecologically sensitive periods, such as calving and energetically sensitive periods. While it is biologically plausible that disturbance during these phases could impact mother-calf relationships and energy management, such effects have not yet been specifically investigated for decommissioning activities. This limits the evidence base for seasonal mitigation measures and leads to a careful, yet uncertain, precautionary approach.

Finally, there is limited knowledge regarding the effectiveness of mitigation measures such as temporary precautionary zones specifically for decommissioning noise. Although this measurement is used and recommended, the effectiveness has primarily been evaluated in the context of impact piling and not for the lower noise levels and other noise characteristics typical of decommissioning.

7.3.2 Seals

For seals, an important knowledge gap concerns the long-term effects of repeated or cumulative disturbance. While Russel et al. (2016) suggest that seals often return relatively quickly to temporarily disturbed areas, it remains unclear how repeated exposure to noise or vibration, for example from multiple decommissioning projects in the same region, may affect spatial use, habitat preference, or foraging behavior over longer time scales.

Furthermore, there is limited knowledge about the thresholds for behavioral change in seals during decommissioning activities. Because seals are less sensitive to underwater noise than harbor porpoises, effects are often considered limited, but the precise noise levels at which disturbance occurs are insufficiently quantified for the relevant noise sources during decommissioning.

Specific evaluation of the effectiveness and proportionality of mitigation measures, such as the use of ADDs in combination with monitoring, is also lacking for seals. Without this knowledge, it remains difficult to optimally tailor measures to the expected effects and to prevent unnecessary disturbance.

8. Marine Life

This chapter describes the potential ecological impacts of OWFs decommissioning on the marine ecosystem. It addresses the effects of removing hard substrates, such as foundations and scour protection, on local biodiversity, as well as the extent and ecological relevance of temporary sediment disturbance. This sediment disturbance can occur during dismantling activities and has potential consequences for benthic organisms and fish populations, both in and around the OWFs and along the cables.

In line with the Dutch legal framework, which prioritizes the complete removal of OWFs, this chapter primarily examines the scenario in which foundations, scour protection, and cables are completely removed. The ecological impacts of these interventions are placed in the context of the current ecological function of OWFs.

In addition to disruption, OWFs can also have potentially positive ecological effects. The introduction of foundations and scour protection creates new hard substrates in a North Sea that is largely characterized by soft, mobile sediments (Degraer et al., 2020). This leads to changes in the benthos and in demersal and bentho-pelagic fish communities (Dannheim et al., 2020). The totality of effects below the sea surface is often summarized as the ‘artificial reef effect’ (Degraer et al., 2020).

Artificial reefs are man-made structures that mimic the properties of natural reefs. Although some reefs are deliberately constructed to stimulate biodiversity and fish species, reef-like habitats are now also emerging as a side effect of the increase in human structures at sea, including oil and gas platforms and OWFs. OWFs provide two types of habitat (Figure 3): vertical hard surfaces (monopiles) and complex horizontal habitats (scour protection), which together create niches throughout the water column, from the splash zone to the seabed (Degraer et al., 2020).

After installation, submerged parts are usually quickly colonized by fouling organisms. Clear vertical zoning occurs on foundations, with species groups differing between shallow zones and deeper parts (De Mesel et al., 2015). In the southern North Sea, OWFs can also form a new offshore habitat for species that normally require hard substrate near the water surface, such as mussels, and indirectly provide opportunities for larger predators such as crabs and lobsters (Degraer et al., 2020). On the scale of a single turbine, biomass can increase significantly compared to the original sediment community (Rumes et al., 2013). These structures can also influence communities on nearby natural hard substrates through changes in species composition and interactions (Wilhelmsson and Malm, 2008).

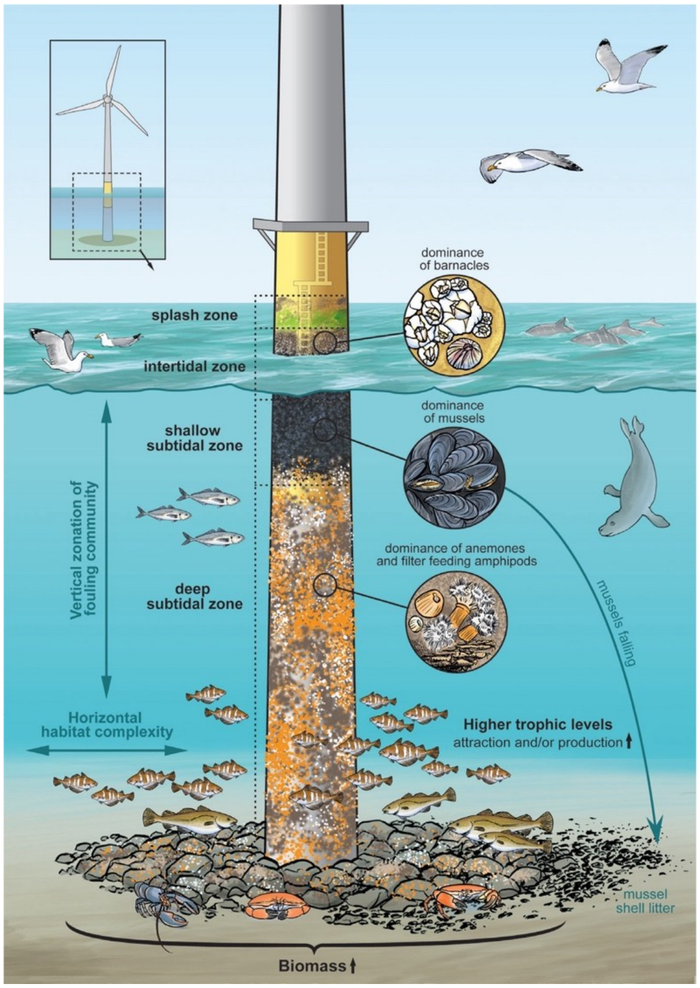

Figure 3: Offshore wind farm structures provide habitat for fouling invertebrates along the depth gradient, thereby attracting predatory fish, seabirds, and marine mammals (Degraer et al., 2020). Illustration by Hendrik Gheerardyn.

In the longer term, the initial colonization can transition into a species-rich, structured community, with Degraer et al. (2020) describing succession stages from pioneer to intermediate and climax communities (Figure 4). At the same time, the presence of new hard habitats may offer opportunities for non-native species, especially in the splash zone and intertidal zone, and the network of structures may facilitate the spread of hard substrate species via a 'steppingstones effect' (Adams et al., 2014). Understanding this habitat function and species role is relevant for decommissioning choices, because removal or retention of structures directly determines the extent to which such reef communities and associated ecosystem functions disappear or persist (Fowler et al., 2020).

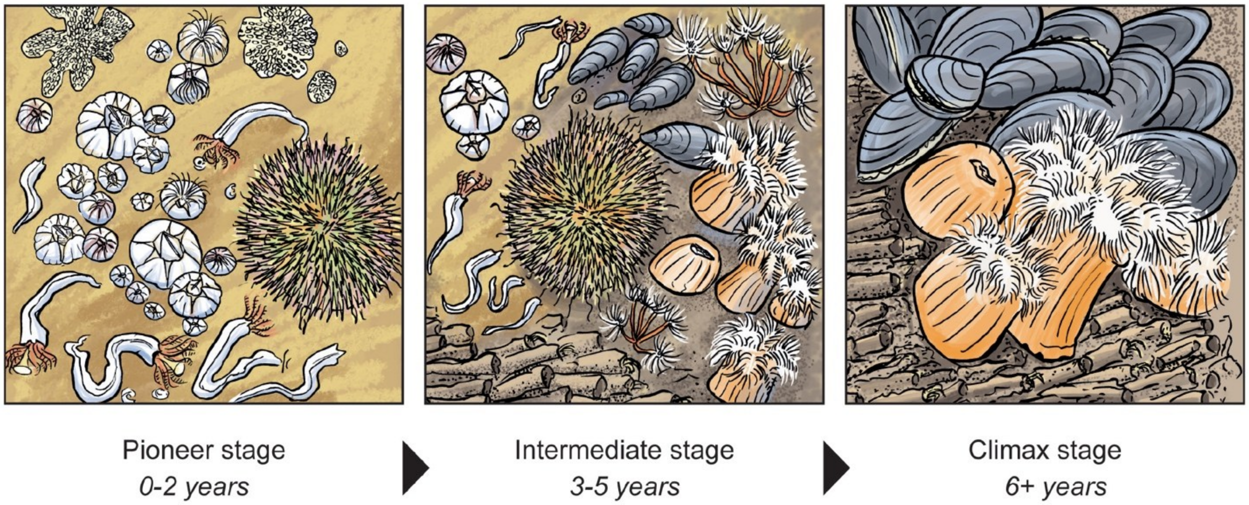

Figure 4: The colonization of offshore wind turbines occurs in stages of succession: a pioneer phase with a limited number of species, followed by an intermediate phase with high species diversity, and finally a climax phase dominated by mussels and sea anemones (Degraer et al., 2020). Illustration by Hendrik Gheerardyn.

8.1 Ecological effects

According to Spielmann et al. (2023), complete decommissioning, involving the removal of both foundations and scour protection, leads to the complete disappearance of the hard substrate biodiversity that developed during the operational phase. In this scenario, the "added" reef habitat is removed, causing epibenthic species to lose their habitat and local populations to disappear.

Although the original soft-bottom habitat may recover over time, Coolen et al. (2020a) emphasize that this recovery does not equate to ecological neutrality. According to Coolen et al. (2020a), the newly created reef communities represent a different functional component of the ecosystem, with higher biomass, altered food web structures, and potential significance for species of commercial or ecological importance. Fowler et al. (2020) point out that complete removal therefore involves a fundamental trade-off between restoring historical conditions and preserving marine habitats that have since developed.

The literature by Spielmann et al. (2023) shows that leaving scour protection in situ is an important factor in preserving local biodiversity. Scenarios in which foundations are removed or cut off, but scour protection remains in place, preserve an average of approximately 70–80% of epibenthic species. This finding is consistent with previous studies on oil and gas platforms, where scour protection also accounts for the largest share of hard substrate biodiversity (Coolen et al., 2020a).

Stranddorf et al. (2026) and Fowler et al. (2020) emphasize that partial decommissioning can significantly reduce the ecological impact, as habitat complexity, shelters, and foraging structures are largely preserved. At the same time, it is recognized that foundation parts above the seabed harbor relatively few unique species when scour protection is present, which may limit the ecological benefit of leaving vertical structures in place (Spielmann et al., 2023).

The presence of hard substrates affects not only benthic invertebrates, but also fish communities and predators in higher trophic levels. Coolen et al. (2020b) and Spielmann et al. (2023) describe that seabed protection and the lower parts of the monopile form important foraging areas for demersal fish species, including cod *(Gadus morhua),* because prey species such as amphipods and small crustaceans are concentrated here.

Removing OWFs can lead to a loss of shelter and foraging habitat, with potential consequences for local fish densities. Fowler et al. (2020) point out that these effects are often insufficiently taken into account in decommissioning decision-making, even though they may be ecologically relevant, especially when the removal of OWFs is followed by renewed fishing activity in the area.

OWFs can also function as habitats and potential dispersal routes for non-native species, particularly in the shallow parts of the monopile (Coolen et al., 2020b; Spielmann et al., 2023). Under full decommissioning scenarios, the removal of these structures eliminates such habitats and may therefore reduce opportunities for further spread of non-native species. This effect should be regarded as an ecological consequence of OWF decommissioning.

8.2 Mitigation measures

In contrast to the construction phase of OWFs, where mitigation measures often focus on limiting acute disturbance (e.g., noise, pile driving), the core of ecological mitigation during decommissioning lies primarily in strategic choices about the scope and method of removal. The literature, including Coolen et al. (2020), Spielmann et al. (2023) and Fowler et al. (2020), emphasize that the greatest ecological effects of decommissioning are related to habitat loss of hard substrates and sediment disturbance, and that this is precisely where the most important points of action for mitigation lie.

In this context, mitigation should not be understood exclusively as an operational measure during implementation, but as an integral part of the decommissioning scenario, in which ecological, technical, and social interests are weighed against each other (Fowler et al., 2020).

Scour protection and foundation retention

The most substantiated mitigation measure in the literature is the (partial) abandonment of scour protection. Spielmann et al. (2023) demonstrate that leaving scour protection in place preserves on average approximately 70–80% of local epibenthic species, depending on the scenario chosen. This confirms earlier findings by Coolen et al. (2020a, 2020b), who identify scour protection as the most ecologically valuable element of offshore infrastructure.
Scour protection is a key habitat for hard substrate species because it provides a high level of habitat complexity with cavities, shelters, and substrate size variation. A significant portion of the reef population formed during the operational phase is preserved by maintaining this structure, which also prevents significant seabed disturbance from removal (Spielmann et al., 2023).

When complete removal of foundations is not strictly necessary, cutting foundations below or just above the seabed can be considered as additional mitigation. According to Spielmann et al. (2023), leaving foundation parts above the seabed contributes only marginally to additional species conservation when scour protection is in place.

Fowler et al. (2020) place this measure in a broader context: retaining foundation parts can be ecologically beneficial, but must be weighed against safety, future redevelopment of the area, and liability issues. Mitigation is therefore context-dependent and requires location-specific decision-making.

Seabed disturbance

Fowler et al. (2020) and Spielmann et al. (2023) emphasize the significance of limiting seabed disruption when full decommissioning of OWFs is required. Temporary increases in turbidity, sedimentation on nearby habitats, and disturbance of soft-bottom communities are all consequences of seabed disturbance. The intensity and spatial breadth of the disruption might vary significantly depending on the technique employed, recovery generally occurs relatively quickly for soft-bottom benthic communities, whereas hard substrate communities do not recover, as their habitat is permanently lost (Birchenough & Degraer, 2020; Spielmann et al., 2023).

Mitigation strategies include, for example, avoiding large-scale displacement or dispersion of rock dumping, limiting the number and duration of heavy anchor and jack-up operations, and applying removal techniques that limit the footprint of the intervention. Although the literature and stakeholder interviews does not prescribe a standardized “best practice,” it consistently emphasizes that method selection is important.

Cables
Sediment disturbance can occur along cable routes due to the excavation or removal of cables. Coolen et al. (2020b), Fowler et al. (2020), and stakeholder interviews describe these effects as local and temporary but emphasize that accumulation is possible when multiple cables are removed simultaneously. Mitigating measures for this could include phased cable removal.

Ecological timing
Although the available literature is limited in formulating specific time windows, Spielmann et al. (2023) and Fowler et al. (2020) point out that the timing of decommissioning can influence ecological effects. Avoiding periods for example with very high reproductive activity of benthic species, peaks in larval dispersion, and seasonal concentrations of fish species can help limit ecological disruption. However, this measure requires location- and species-specific knowledge, which is often lacking.

Habitat
Coolen et al. (2020a, 2020b) and Spielmann et al. (2023) demonstrate that scour protection and low foundation sections are important foraging and sheltering habitats for demersal fish species. Mitigation measures for marine life can, in this context, not prevent habitat loss but should focus on limiting additional impacts, for example through careful timing of activities and by considering the combined effects of habitat removal and the potential reopening of OWF areas to fishing, which may indirectly affect local fish populations.

8.3 Knowledge gaps

The ecological effects of the construction and operational phases of OWFs have been relatively well researched. A number of papers have already been written on benthos, but there is a knowledge gap regarding the ecological consequences of decommissioning. As a result, current knowledge is largely based on indirect analyses (modeling, scenario comparisons), comparisons with oil and gas, and ecological data from the operational phase.

A major knowledge gap concerns the lack of harmonized, long-term monitoring programs for OWFs in Europe. Existing datasets vary greatly between countries and projects in terms of, for example, sampling methods, sampling depths, focus on foundations versus seabed protection, and monitoring over time. It is challenging to draw conclusions regarding the ecological effects of decommissioning and to compare areas due to the disparity in monitoring systems.

Another knowledge gap is the lack of ecological data immediately before and during the decommissioning phase. Spielmann et al. (2023) emphasize that monitoring programs often stop or scale down in the later operational phase, even though this period is crucial for recording the mature state of reef communities, correctly interpreting succession stages, and establishing a reliable ecological baseline for decommissioning. Without this data, it is difficult to distinguish the effects of decommissioning from natural dynamics or long-term changes in the ecosystem.

Although several studies show that OWFs lead to high biomasses of filter feeders and changes in local species composition, there is still insufficient insight into the functional implications of this for the wider ecosystem. The role of OWFs in secondary production, the degree to which increased benthic biomass causes structural changes in food webs, and the effects of the sudden removal of these structures on nutrient flows and energy transfer between benthos and higher trophic levels are some specific knowledge gaps.

The available literature suggests that OWFs provide foraging and sheltering habitats for demersal and bentho-pelagic fish species, partly due to the combination of habitat complexity and fishing exclusion. At the same time, according to Fowler et al. (2020) and Spielmann et al. (2023), there is insufficient evidence to determine the extent to which the increased fish densities around OWFs are the result of actual population growth ("production") or merely redistribution ("attraction"). There is also insufficient evidence of the indirect effects that may occur as a result of the removal of no-fishing zones after decommissioning. It is challenging to estimate the ecological impact of decommissioning on fish populations at the regional level due to these uncertainties.

Although sediment disturbance during decommissioning is generally considered to be temporary and local, Spielmann et al. (2023) and Fowler et al. (2020) point out that the ecological significance of this disturbance is highly context dependent. The intensity, spatial extent and duration of impacts depend strongly on the techniques applied, including whether decommissioning involves dredging, cutting, or vibration-based methods such as vibratory pile extraction. There is limited knowledge about the effects of such vibration-based techniques on benthic communities and fish, particularly with respect to behavioral responses, displacement, and recovery times. In addition, there is little understanding of the recovery of soft-bottom communities following repeated or large-scale disturbance, or of the interactions between sediment disturbance and other stressors (e.g. climate change and fishing).

Another knowledge gap concerns the cumulative effects when multiple OWFs are dismantled in a short period of time. Systematic ecological effects are also lacking along cable routes, where disturbance can occur linearly and diffusely.

The literature suggests that OWFs may function as nodes in a network of hard substrates, thereby influencing species dispersal and connectivity. At the same time, there is little quantitative insight into the contribution of individual OWF to regional population connectivity, the role of specific structures as habitat, and the consequences of large-scale removal of structures for dispersal routes. This knowledge gap is particularly relevant in the North Sea, where the expansion and future decommissioning of OWFs is being carried out on a large scale.

Non-native species can be found on offshore structures, particularly in shallow zones, but there is insufficient understanding of the role of OWFs in the large-scale spread of these species. There is also no knowledge about the effects of partial versus complete decommissioning on non-native populations, nor is there any knowledge about the extent to which decommissioning can contribute to limiting or, conversely, promoting further dispersal. It is challenging to incorporate non-native species into ecological issues related to decommissioning because of this uncertainty.

A final, overarching knowledge gap concerns the lack of a coherent, long-term vision for the North Sea as a whole. Although individual OWFs are assessed and managed at the project level, a broadly supported reference framework clarifying the desired future ecological status of the North Sea in light of large-scale offshore wind energy deployment and future decommissioning is lacking. It is unclear whether management should focus on restoring the original sandy seabed, preserving newly created hard-substrate habitats, or actively deploying OWFs as a tool for nature restoration and biodiversity enhancement. This lack of an integrated, ecosystem-wide vision complicates the assessment of decommissioning scenarios, as the "preferred outcome" depends heavily on the chosen reference state and long-term policy goals. Without an explicitly formulated North Sea vision that connects the energy transition, biodiversity goals, and marine spatial planning, there is a risk that decommissioning decisions will be made in a fragmented and reactive manner, rather than as part of a strategic, ecosystem-based approach.

9. Indirect and Cumulative Effects

This chapter focuses on the indirect and cumulative ecological impacts of decommissioning OWFs. While previous chapters focused primarily on the direct, local effects of individual decommissioning activities, this chapter shifts its focus to broader and longer lasting consequences at the ecosystem. Indirect effects can occur when disturbances do not directly affect species, but still affect the system through changes in habitats, food webs, or ecological processes.

Furthermore, cumulative effects are important when multiple OWFs are decommissioned during the same period, when decommissioning coincides with other human activities at sea (such as shipping, fishing, or sand extraction), or when effects accumulate over time and space. Although individual decommissioning activities are often considered temporary and local, such effects can become ecologically significant when they occur simultaneously or repeatedly.

Finally, the question of the extent to which the marine ecosystem returns to its original state after decommissioning is addressed. This consideration includes not only physical recovery processes of the seabed but also the extent to which ecological functions and species compositions correspond to the situation before the OWF was constructed. This chapter therefore places the long-term and cumulative effects of OWF decommissioning within a broader ecological perspective.

9.1 Ecological effects

9.1.1 Indirect

The indirect ecological effects of OWF decommissioning are not primarily expressed as a clear increase or decrease in biodiversity, but rather as changes in ecosystem structure and functioning. During the operational phase, OWFs introduce hard substrates into environments that are predominantly characterized by soft sediments, facilitating the development of reef like communities associated with monopiles and scour protection (Coolen et al., 2020; Spielmann et al., 2023). Decommissioning will reverse this situation, shifting the system back towards a soft-bottom dominated state.

These indirect effects therefore relate mainly to functional ecosystem changes, including:

- Species composition, with a transition from epibenthic hard substrate communities to infaunal soft-bottom assemblages.
- Habitat functionality, such as the loss of attachment surfaces, shelter, and nursery functions associated with hard substrates.
- Food web structure, as the removal of filtering epifauna and associated secondary production affects predator–prey interactions and energy transfer within the system.

Fowler et al. (2020) emphasize that such indirect effects can be ecologically relevant even when changes in total species richness at a regional scale remain limited. The ecological consequence of decommissioning therefore lies less in a simple loss or gain of species, and more in a shift in community type and associated ecosystem processes, including food-web dynamics.

Indirect effects are not restricted to the physical footprint of monopiles, scour protection, or cables. Decommissioning activities can induce process driven impacts, such as sediment resuspension, increased turbidity, and sediment plume dispersion, which may influence surrounding habitats beyond the immediate removal area (Spielmann et al., 2023; Fowler et al., 2020). These effects can result in temporary smothering of adjacent soft-bottom habitats, reduced performance of filter-feeding organisms, and altered foraging conditions for mobile species, including demersal fish.

Importantly, these impacts are both spatial and temporal in nature. Disturbance zones may overlap spatially when multiple turbines are decommissioned simultaneously, while temporally the effects may persist beyond the active removal phase due to delayed recolonization and recovery processes. The magnitude and ecological relevance of these indirect effects are strongly context dependent and influenced by factors such as location, sediment type, hydrodynamic conditions, and season. For example, the ecological consequences of sediment plumes may differ substantially depending on background turbidity levels and seasonal sensitivity of primary production or benthic communities.

Overall, indirect effects of OWF decommissioning should therefore be understood as ecosystem responses, driven by changes in habitat structure, ecological processes, and food web interactions, rather than as straightforward changes in biodiversity indicators alone.

9.1.2 Cumulative

A key focus in the literature is the accumulation of pressure factors when multiple OWFs are decommissioned within the same period, but cumulative effects may also arise when decommissioning coincides spatially or temporally with the construction or operation of other OWFs. Gușatu et al. (2021) show that individual pressure factors that are limited in scale can become ecologically relevant when they accumulate in time and space, regardless of whether they originate from similar or different project phases.

Potential cumulative effects therefore occur not only when multiple decommissioning activities take place simultaneously or in quick succession, but also when decommissioning overlaps with activities such as pile driving, cable installation, or ongoing operational disturbances in nearby OWFs. In such situations, there may be a combined increase in shipping movements, underwater noise, and sediment disturbance, thereby extending both the spatial and temporal footprint of ecological pressure.

Overlapping recovery and disturbance phases may result in cumulative ecological effects. For example, benthic communities in one area may still be recovering from construction related impacts while nearby areas experience new disturbances from decommissioning activities, leading to temporal and spatial overlap. This overlap can hinder or delay natural recovery processes, particularly in ecosystems where recolonization rates are slow. For highly mobile species such as fish, marine mammals, birds, and bats, the presence of multiple disturbance sites during construction, operation, and decommissioning can increase avoidance behavior, potentially altering foraging patterns, energy expenditure, and spatial distribution.

The accumulation of these pressures can have significant ecological consequences, particularly for species and communities with low recovery capacity or limited dispersal ability, even when individual activities are considered local and temporary in isolation.

According to the literature, the extent to which ecosystems return to their original state following complete removal of an OWF remains largely uncertain. The duration of the operational phase influences how strongly hard substrate communities have developed and how deeply they have become integrated into local ecosystem functioning. In addition, the intensity and nature of physical disturbance during decommissioning plays an important role. For example, large-scale seabed disturbance and complete removal of structures may delay recovery times or lead to alternative post disturbance states. Finally, the regional context is important, including the presence of other natural or anthropogenic hard substrates, such as nearby operational OWFs, which may act as sources for recolonization and thereby influence whether recovery leads to conditions comparable to the pre-installation state.

9.2 Mitigation measures

A key mitigating measure against cumulative impacts is the coordination of decommissioning in time and space, in overlap with other offshore activities. Spreading decommissioning activities can prevent multiple OWFs from simultaneously exerting ecological pressure on the same system. This is particularly relevant in the North Sea, where many OWFs reach the end of their lifespan within a relatively short timeframe. However, cumulative impacts can also arise when decommissioning overlaps with the construction of new OWFs or with disturbances from operational OWFs. In such cases, similar pressures, such as shipping, underwater noise, and bottom disturbance, can accumulate, despite resulting from different project phases.

As discussed previously in Chapter 8 (Marine Life), retaining scour protection and, in some cases, parts of the foundations can play a significant role in limiting the indirect and cumulative ecological impacts of decommissioning, provided that the preservation of hard substrate communities is considered an ecological objective. By leaving these structures in situ, habitat functionality for hard substrate species is largely preserved, while large-scale seabed disturbance resulting from removal activities is avoided. This can shorten or, in some cases, largely prevent the recovery processes of benthic communities. From a cumulative perspective, this approach can contribute to mitigating regional ecological effects, particularly when multiple OWFs are dismantled during the same period or when dismantling coincides with new construction activities.

However, implementing such measures requires a clear vision of the desired development of soft- and hard substrate communities at a regional scale. Choices regarding the retention or removal of structures are not value neutral but largely determine which ecosystems are supported in the long term. This consideration is particularly relevant for future decommissioning projects.

Lindenmayer & Likens (2010) and Mieszkowska et al. (2014), cited in Fowler et al. (2020), emphasize the importance of adaptive management in situations of high uncertainty. For decommissioning, this primarily means that monitoring prior to and during decommissioning can be used to identify unforeseen indirect or cumulative effects, for example, in relation to seasonally sensitive species or ecologically sensitive periods. However, the opportunities for fundamental adjustments during implementation are often limited, meaning that adaptive management primarily plays a role in improving decision-making and mitigation strategies for future decommissioning activities, rather than correcting ongoing interventions.

9.3 Knowledge gaps

Field data on the indirect and cumulative effects of decommissioning are largely lacking. Most conclusions are based on modeling, extrapolation, or analogies with other sectors, which means that uncertainty remains a key feature.

There is limited knowledge about the recovery time and direction of ecosystems when multiple disturbances follow each other. In particular, the question of whether ecosystems return to their original state or assume an alternative stable state has not been sufficiently researched.

Gușatu et al. (2021) show that cumulative impact assessments for OWFs largely focus on construction and operation. Decommissioning is often not explicitly included in these assessments, resulting in a knowledge gap in policy and decision-making frameworks.

10. Uncertainties

Decommissioning of OWFs represents a relatively new and poorly documented phase in the life cycle of offshore energy infrastructure, resulting in substantial uncertainties when this phase is incorporated into future KEC assessments. In contrast to construction and operation, data on ecological impacts of decommissioning are limited, as only a small number of OWFs have been decommissioned to date, often at small scale and without harmonized, long-term ecological monitoring. As a result, current impact assessments largely rely on analogies with oil and gas infrastructure, modelling approaches, and estimations from the construction and operational phase data, which introduces uncertainty in impact magnitude, spatial extent, and recovery pathways. Additional uncertainty arises from the fact that decommissioning techniques are still under development and may differ substantially in terms of seabed disturbance, noise emissions, and material removal. Moreover, in the Netherlands and other North Sea countries, there is ongoing policy uncertainty regarding the required scope of decommissioning, particularly with respect to the removal or retention of scour protection and infield cables. These technical and regulatory uncertainties complicate the definition of realistic decommissioning scenarios within the KEC framework and highlight the need for adaptive assessments that explicitly account for scenario variability, knowledge gaps, and evolving policy and technological contexts.

The main uncertainties surrounding the decommissioning of OWFs can be grouped into three interrelated categories.

The first category concerns knowledge uncertainty. This includes the limited understanding of ecological processes and responses during and after decommissioning. Key knowledge gaps relate to the lack of data on mature reef communities immediately prior to decommissioning, uncertainty about recovery pathways following the removal of hard substrates, and limited insight into indirect effects on food webs, fish populations, and broader ecosystem functions. In addition, marine ecosystems in the North Sea differ strongly in terms of species composition, sediment characteristics, and hydrodynamic conditions. While such variability is inherent to marine systems, it remains uncertain to what extent and in which ways ecological responses to decommissioning differ between ecosystem types, and how these differences influence recovery processes.

The second category relates to technical and market-related uncertainty. Decommissioning techniques for OWFs are still under development, and multiple approaches are being explored by different developers and contractors. In addition, different monopile/foundation types require different removal techniques. For example, the early generation of monopiles may require alternative decommissioning techniques compared to more modern, larger monopiles. These technical differences can influence the duration of activities, the type and level of noise generated, and the extent of seabed disturbance.

As a result, there is limited transparency regarding the exact methods that are likely to be applied in future decommissioning projects. Commercial sensitivities and ongoing innovation mean that detailed information on operational procedures, disturbance levels, and mitigation measures is often not publicly available. This uncertainty about how decommissioning will be carried out directly translates into uncertainty about the nature and magnitude of ecological effects.

The third category concerns scenario and scale uncertainty. The ecological consequences of decommissioning depend strongly on the selected decommissioning scenario (e.g. complete versus partial removal), the timing of activities, and the spatial and temporal overlap of multiple decommissioning projects. Furthermore, decommissioning schedules are highly dependent on metocean conditions. Weather-related delays represent a significant uncertainty factor in the decommissioning of OWFs. Simulation-based analyses show that weather sensitivity can explain 15–40% of the campaign costs, depending on the subsystem considered (Mancini, 2026). From an ecological perspective, this means that the actual timing and seasonal overlap of decommissioning activities are not fully controllable, increasing the likelihood that work will coincide with ecologically sensitive periods, such as migration, spawning, or breeding seasons.

In addition, there is particular uncertainty regarding threshold values and the recovery capacity of populations and habitats when decommissioning occurs at larger spatial scales or in combination with other pressures. This complicates the assessment of cumulative effects at a regional level and limits the ability to draw robust conclusions within the KEC framework.

10.1 KEC framework

The KEC framework, or Framework for Assessing Ecological and Cumulative Effects, is a Dutch scientific tool to evaluate the environmental impacts of OWF development in the North Sea. It was primarily developed to systematically assess the cumulative ecological effects of offshore wind energy based on pressure-effect relationships, the sensitivity of ecological components, and accumulation over time and space.

When incorporating decommissioning into future KEC assessments, it is essential to explicitly establish for each KEC: Which effects are empirically substantiated? Which effects are primarily based on modeling, analogies, or expert judgment? And where are there significant knowledge gaps?
By explicitly documenting uncertainty for each ecological component, knowledge gaps are prevented from being implicitly interpreted as an absence of effect.

Given the limited knowledge base, it is recommended that the KEC framework can work with worst case scenarios and ranges rather than point estimates. This is particularly relevant for cumulative effects, where the simultaneous occurrence of multiple decommissioning activities, OWF construction, or other North Sea activities (such as fisheries or sand extraction) may spatially and temporally overlap. If only average effect estimates are applied, this overlap may result in a structural underestimation of the total ecological pressure.

The KEC framework can be used to analytically compare different decommissioning scenarios, for example, complete removal versus leaving scour protection in place. By comparing scenarios, insight can be gained into the sensitivity of ecological components to assumptions and uncertainties in design and implementation choices. This comparison is exploratory and knowledge-building and does not imply policy discretion or deviation from applicable laws and regulations or site decisions. Any updates to KEC analyses based on new results can be used to increase the general level of knowledge and support future policy frameworks and assessment methodologies, without leading to interim adjustments to permitted obligations for existing OWFs.

10.2 Monitoring and adaptive management

Linking decommissioning to targeted monitoring can help reduce uncertainties, but it should be embedded in the existing policy and permitting structure. In practice, the preconditions for decommissioning are established in the site decision and the associated permits, often decades before actual decommissioning takes place. This makes it unrealistic to impose stricter or more costly decommissioning measures on existing OWFs based on new ecological insights. The value of monitoring, therefore, lies primarily in generating knowledge at the system level, which can be used to test assumptions from KEC analyses and better inform future site decisions, policy frameworks, and decommissioning guidelines. In this approach, monitoring serves as input for long-term learning and adaptive policies, without introducing legal or financial uncertainty for existing permit holders.

10.3 Future KEC assessments

Integrating decommissioning into future KEC assessments requires a shift from a point-in-time impact assessment to a more process-oriented approach. Recent developments in the KEC methodology, particularly for determining impacts on birds, have led to increasing attention being given to the entire life cycle of an OWF, including the post-operational phase. Currently, this life cycle approach is primarily limited to the point at which an OWFs is no longer operational, and the actual ecological effects of decommissioning are not explicitly considered. However, this does demonstrate that there is room within the KEC framework to explicitly address decommissioning. It is essential that uncertainties and knowledge gaps are not masked but presented explicitly and transparently. This allows policymakers and permitting authorities to gain insight into the robustness of the conclusions, the potential risks of cumulative effects, for example, in the case of simultaneous decommissioning of multiple OWFs or in combination with the construction of new OWFs, and the extent to which additional monitoring and adaptive measures are necessary. By explicitly incorporating uncertainty into the KEC framework, decommissioning can be incorporated into the assessment of the ecological impacts of offshore wind energy in the North Sea in a consistent and scientifically sound manner.

10.4 KEC matrix

Table 3 shows that the ecological impacts of OWF decommissioning vary greatly in spatial scale, temporal persistence, and degree of uncertainty across different pressures and species groups. Structural interventions, such as the complete removal of foundations and scour protection, as well as scenarios in which multiple OWFs are simultaneously decommissioned or constructed, are associated with a high degree of uncertainty. This reflects the limited number of observations from actual decommissioning projects and the complexity of indirect and cumulative impact pathways, where changes in habitat structure, food web dynamics, and spatial use can reinforce each other.

At the same time, Table 3 makes it clear that temporary disturbances, such as sediment resuspension and increased shipping activity, are predominantly local and short-lived. Nevertheless, these impacts can become ecologically significant when they accumulate over time and space, for example, with the simultaneous decommissioning of multiple OWFs or in combination with other offshore activities.

The interpretation of the temporal persistence of impacts in Table 3 is clarified in Table 2, which systematically defines the terms used. A distinction is made between short-, medium-, and long term effects, as well as permanent effects that are irreversible within a policy or ecological time horizon. Table 2 also explains the concepts of the attraction hypothesis and the production hypothesis, which are relevant for assessing effects on fish populations. This distinction is important for determining whether increased fish densities around OWFs are the result of redistribution (attraction) or of actual biomass increases (production), which has direct implications for the ecological significance of removal.

Table 2: Explanation of terms used in Table 3.

Terms	Meaning
Short term	Days – weeks: full recovery expected.
Medium term	Months – years: recovery likely.
Long term	Years – decades: structural change but theoretical recovery possible.
Permanent	Irreversible within policy or ecological timescale.
Attraction hypothesis	Fish concentrate around OWF, but total population does not grow.
Production hypothesis	OWF increases total biomass (more survival/recruitment).

Furthermore, Table 3 addresses the importance of explicitly and transparently addressing uncertainties in future KEC assessments. By clarifying, for each ecological component, where knowledge is robust and where assumptions, modeling, or expert judgment dominate, the matrix supports more consistent and informed decision-making regarding decommissioning. Uncertainty is not considered an obstacle, but an explicit component of the analysis that can guide scenario choices, monitoring priorities, and adaptive management.

The KEC matrix is therefore an essential tool for systematically and ecologically integrating the decommissioning of OWFs into cumulative impact assessments for the North Sea.

Table 3: Summary overview of ecological effects of decommissioning OWFs per species group.

Decommissioning pressure	Species	Potential ecological effect	Spatial scale	Temporal persistence of ecological effect	Knowledge gap
Increased vessel traffic, lighting and presence of activities	Seabirds	Disturbance of resting and foraging behavior, temporary displacement	Local → regional	Short term	Uncertainty regarding disturbance versus habituation
Removal of OWF structures	Seabirds	Loss of indirect foraging opportunities (via fish/benthos), altered spatial use, no turbine collisions	Regional	Medium term	Insufficient knowledge of the functional role of OWFs for seabirds, recolonization uncertainty
Lighting, vessel traffic and activities during migration	Migratory birds	Disorientation, increased energetic costs, temporary rerouting of migration	Regional	Short term	Limited data specific to the decommissioning phase
Lighting, vessel traffic and operational activities	Bats	Disturbance and avoidance behavior, uncertain attraction or avoidance, low collision risk	Regional	Short term	Major knowledge gap, offshore behavior unknown

Removal of OWF structures	Bats	Loss of potential offshore resting or orientation structures, no turbine collisions	Regional	Short term	High uncertainty regarding ecological relevance of OWFs for bats
Continuous underwater noise (cutting, stone removal, hydraulic extraction)	Marine mammals	Behavioral avoidance: disturbance near resting/foraging areas, risk of TTS (low), PTS (unlikely but not impossible under certain techniques), mother–calf separation risk (low but possible), cumulative exposure	Local → regional	Mixed (Disturbance on short term, PTS permanent if it occurs)	Limited decommissioning specific exposure-response data, threshold unclear, lack of decommissioning noise measurements
Increased vessel traffic & surface noise	Marine mammals	Temporary disturbance, avoidance behavior,	Regional	Short term	Limited decommissioning-specific acoustic data
Removal of hard substrates (monopiles + scour protection)	Epibenthic macrofauna	Permanent loss of hard-substrate habitat, loss of reef succession stages, shift to soft-bottom assemblages, food web restructuring	Local → regional (if multiple OWFs)	Permanent (habitat loss)	Limited decommissioning data, unclear regional food web consequences
Removal of hard substrates (monopiles + scour protection)	Demersal and benthos-pelagic fish	Reduction of shelter and foraging habitat, altered predator–prey dynamics	Local → regional	Medium–long term (dependent on production vs attraction)	Uncertainty regarding production hypothesis versus attraction hypothesis and population-scale effects
Removal of scour protection only	Epibenthic macrofauna	Loss of ~70–80% of hard substrate species	Local	Permanent	Scenario-specific data limited
Seabed disturbance and sediment resuspension (scour protection + cables)	Soft-bottom benthic communities	Temporary reduction in abundance and species richness, recovery through succession	Local / linear (cable routes)	Short to medium term	Uncertainty regarding recovery time under repeated or cumulative disturbance
Seabed disturbance and increased turbidity	Fish (all life stages)	Temporary disruption of foraging and migratory behavior	Local → regional	Short term	Uncertainty regarding magnitude and spatial extent of additional turbidity under varying sediment and hydrodynamic conditions
Re-opening of area to bottom trawling after decommissioning	Soft-bottom benthos + demersal fish (and food web)	Increased seabed disturbance, reduced recovery potential, loss of OWF “refuge effect”	Regional	Long term (depends on fishing intensity)	Timing of fishing return, combined effect with habitat removal
Simultaneous decommissioning of multiple OWFs	All species groups	Overlapping recovery periods, increased ecosystem pressure, for birds and bats cumulative disturbance along migration routes	Regional → North Sea scale	Medium term	High uncertainty: cumulative effects poorly studied, cumulative thresholds largely unknown
Retention versus removal of structures	*Non-indigenous species	Retention may maintain stepping-stone connectivity: full removal may reduce habitat and dispersal opportunities (especially shallow zones)	Regional	Long term	Uncertainty regarding the role of OWFs in large-scale species spread, net effect depends on which structures remain (splash/intertidal vs deep), limited evidence

*Non-indigenous species: Complete removal potentially limits the spread of invasive species, which is positive for the North Sea ecosystem. Therefore, the effect depends on the chosen decommissioning scenario.

11. Conclusion

The decommissioning of OWFs is an important, yet understudied, part of the total life cycle of offshore wind energy. While the ecological impacts of construction and operation are being investigated, the decommissioning phase remains characterized by limited knowledge, a high degree of technical uncertainty, and dependence on the chosen decommissioning scenario. This phase is important because the choices made determine both ecological recovery and the long-term spatial use of the North Sea.

The results of this report confirm that decommissioning cannot be considered only as a technical or legal end phase, but rather as an intervention with technological, legal, social, and ecological implications. Furthermore, the decommissioning of OWFs takes place in the North Sea, an area characterized by intensive land use, cumulative pressures, and a rapidly expanding offshore energy sector. This requires an assessment framework that extends beyond individual projects and explicitly considers scale, timing, and overlap with other activities.

The Netherlands currently lacks an integrated long-term ecological vision for the North Sea that considers the phases of construction, operation, and decommissioning in a coherent manner. As a result, decisions about decommissioning are largely made on a project-by-project basis and within existing legal frameworks, without being explicitly embedded in a broader system-oriented ecological strategy.

Although OWFs have an operational lifespan of approximately 40 years, ecological processes, habitat development, and system restoration occur over longer timescales. Without clear long-term goals, for example regarding habitat diversity, restoration of benthic communities or the reduction of cumulative pressure, there is a risk that decommissioning choices will be primarily driven by technical or legal considerations, rather than by an explicit ecological development direction for the North Sea as a whole.

11.1 Scenarios

A central tension in the decommissioning debate concerns the choice between complete removal of OWFs and (partially) leaving them in place, such as a portion of the monopile or scour protection. From an ecological perspective, the literature shows that OWFs lead to the development of artificial reef communities, with a clear shift in species composition compared to the original sandy ecosystem. These communities are generally species rich, but consist primarily of common, opportunistic species that do not necessarily contribute to policy objectives for nature conservation and restoration.

The results of this report align with previous studies indicating that complete removal of infrastructure offers the best starting point for restoring the original soft-bottom ecosystem, especially in areas historically characterized by dynamic sandbanks. At the same time, it is recognized that partial removal can lead to the preservation of existing hard-substrate communities and locally increased biomass, with potential indirect effects on higher trophic levels.

It is important, however, that this “new nature” cannot be treated as nature restoration in a policy sense. The preservation of artificial structures leads to the persistence of a human-introduced habitat, which is difficult to align with objectives aimed at restoring natural processes and habitats. This distinction is important to prevent ecological arguments from being used to legitimize the abandonment of infrastructure without a clear policy justification. A clear ecological vision for the North Sea can clarify whether or not these ecosystems are desirable.

11.2 Techniques

The analysis of decommissioning techniques shows that the practical feasibility of decommissioning scenarios depends on the available technology. This determines the extent to which the legal principle of complete removal can actually be applied. Although the Dutch policy framework clearly outlines the ultimate goal, the complete removal of OWFs, the technical analysis reveals that achieving this goal depends on available technologies that are still under development. In particular, the scale and complexity of modern OWFs make conventional methods, developed for smaller structures or for the oil and gas sector, inapplicable. This creates a clear dependence on technological innovation to make policy objectives achievable in practice.

The analysis of monopile removal shows that complete removal is technically feasible, but currently faces uncertainties. Innovative techniques such as hydraulic extraction, vibration-based methods, and jetting-based methods offer prospects, but are largely still in the research and demonstration phase. This means that scalability to large-scale, modern monopiles with large diameters and varying soil conditions has not yet been demonstrated.

A similar pattern applies to scour protection and cables. Technical removal options are available, but these involve significant logistical effort, significant sediment disturbance, and complex processing processes, especially when reuse or material recovery is the goal. The development of more targeted and less disruptive techniques, such as vibration-based cable removal, demonstrates that it is possible to reduce ecological impact without compromising complete removal. At the same time, this emphasizes the importance of design choices during the construction phase of new OWFs for future decommissioning. By explicitly incorporating decommission ability, circularity, and limited sediment disturbance into the design of foundations, scour protection, and cable systems, future reliance on complex and ecologically disruptive decommissioning techniques can be reduced.

Importantly, different removal techniques are associated with different types and magnitudes of ecological impacts. For example, techniques such as cutting, lifting, dredging, or vibration-based extraction generate different forms of underwater noise (impulsive, continuous, or transmitted via structures), as well as varying degrees of sediment resuspension and spatial disturbance. These differences can influence both the intensity and spatial extent of ecological impacts, particularly for noise-sensitive species such as marine mammals and for benthic communities sensitive to sedimentation. Therefore, the choice of a removal technique should be based not only on technical feasibility and cost, but also on its specific ecological impact.

11.3 Birds & Bats

The results from Chapter 6, Birds & Bats, show that the decommissioning phase is primarily ecologically relevant for this species group as a transition from long-term effects during the operational phase to a short but temporary disturbance during decommissioning. While the operational phase for many seabirds is primarily characterized by long-term functional habitat loss and barrier effects due to avoidance behavior, decommissioning is dominated by short-term, localized disruption caused by increased shipping movements, above water noise, crane activity, and temporary artificial work lighting. This distinction is important because it indicates that impacts during the decommissioning phase are generally less likely to reach population levels than those during the operational phase. Although decommissioning can take longer to complete than the construction phase, the impacts are usually less intense. They often involve temporary and localized disruption, rather than long-term functional habitat loss or high noise levels, such as those associated with pile driving.

However, this may be different when decommissioning activities coincide with ecologically sensitive periods, such as the molting season, winter concentrations, or migration peaks. Cumulative pressure can also increase when multiple OWFs are decommissioned during the same period, or when decommissioning takes place simultaneously with the construction of new OWFs in the same area.

Furthermore, overlap with other human activities in the North Sea, such as shipping, fishing, or sand extraction, can lead to further accumulation of disruption. This underscores the importance of an integrated approach to the different phases of offshore wind energy. Whereas previously effects were often assessed separately per phase (construction or operation), the current scale of development requires an assessment that also explicitly includes decommissioning and analyses temporal and spatial overlap between phases.

An important point is that decommissioning can also represent a structural ecological shift for species that avoid OWFs during the operational phase. The removal of turbines and vertical structures can reclaim previously avoided sea areas, reduce functional habitat loss and potentially enable the recovery of sea use. At the same time, it is uncertain to what extent and how quickly birds will reuse this reclaimed area. Reclaimed habitat does not automatically mean rapid recolonization, especially when avoidance has become established over time or when background pressure (such as shipping, fishing, or nearby operational OWFs) continues to affect the area's suitability.

Furthermore, the ultimate ecological outcome is highly dependent on the area's future purpose. If a new OWFs is constructed after decommissioning, or if the area is used for fishing, oil and gas activities, sand extraction, or military exercises, new pressures arise that can limit or alter potential recovery. Decommissioning should therefore not be viewed only as a temporary disruption, but as a transitional phase in the spatial use of the North Sea. This highlights the importance of a long-term ecological vision for the North Sea, which explicitly addresses not only the construction and operation of OWFs, but also the phase after permits expires. Without a clear development direction for areas after decommissioning, there is a risk that ecological recovery opportunities will be missed or that new cumulative effects will arise. Targeted monitoring after decommissioning is necessary to gain insight into both recovery processes and any new pressures.

For migratory birds and bats, the focus during decommissioning is less on collision risk and more on artificial light-related effects. The decommissioning of OWFs significantly reduces the risk of collisions and for bats barotrauma compared to the operational phase. At the same time, nighttime operations and ship artificial lighting can lead to disorientation, attraction, or even avoidance, especially in poor visibility conditions. This uncertainty is particularly significant for bats: their presence and behavior at sea, and their response to light and human activity, are still insufficiently known to robustly substantiate the direction and magnitude of effects. Therefore, the main conclusion is that decommissioning is likely less risky than the operational phase, but the supporting evidence for this is still weak, and precautionary measures remain appropriate. A mitigation measurement is the use of targeted, shielded, and low-intensity lighting, to avoid unnecessary lighting and limiting the use of continuous, bright lighting.

11.4 Marine Mammals

For marine mammals, the analysis confirms that the ecological impact of decommissioning is generally smaller than that of the construction phase, primarily because pile driving (and thus impulsive, high-intensity noise) is absent. Although explosive techniques have been used in offshore decommissioning in the past, current regulations and increased environmental awareness favor non-explosive removal methods, which reduce the risk of high-intensity impulsive underwater noise. Decommissioning is expected to be characterized primarily by continuous or semi-continuous noise sources, such as lifting and grabbing activities, bottom cultivation, the removal of scour protection, and cable pulling. This does not mean there are no effects, but it does mean that the risk shifts from hearing damage and significant disturbance to primarily behavioral disruption and temporary displacement. The distinction between impulsive and continuous noise is therefore essential for interpreting effects and for the proportionality of any mitigation.

The analysis for harbor porpoises and seals also shows that sensitivity is highly species dependent. Harbor porpoises, due to their strong reliance on echolocation and their high sensitivity to anthropogenic noise, are the species group most likely to experience behavioral effects during decommissioning, even when noise levels are lower than during pile driving. Effects are then primarily expected in the form of temporary avoidance of the work area and interruption of foraging behavior. Regarding seals, the literature is less conclusive, and behavioral adaption appears to be more common. Disturbance is particularly relevant near resting or haul-out areas.

A key limitation, however, remains the unavailability of direct field data on sound and response during the actual decommissioning of OWFs. Interpretation is therefore partly based on analogies with other offshore activities and on more thoroughly investigated effects during the construction phase. This makes it difficult to define disturbance distances, thresholds, and recovery periods with the same degree of certainty as with pile driving. Considering the future decommissioning projects in the Dutch North Sea, the cumulative dimension is particularly relevant. Overlapping decommissioning projects, combined with existing shipping, operational OWFs, and other offshore activities such as seismic surveys for oil and gas exploration, can lead to repeated exposure at the area level. This potentially shifts the risk from a one-off local disturbance to repeated disturbance over space and time.

11.5 Marine Life

Chapter 8, Marine Life, demonstrates that the ecological consequences of dismantling are not solely determined by temporary disturbance, but primarily by a habitat transition. Removing hard substrate reverses the artificial reef effect that developed during the operational phase. This means that the core of the effect is not just captured by disturbance indicators such as turbidity or bottom disturbance, but by the loss of habitat complexity and the associated epibenthic communities. The literature and the analysis in this report confirm that scour protection plays a significant role in this, as this structure supports a large portion of the local hard-substrate biodiversity and provides habitat. The difference between complete removal and the absence of scour protection therefore primarily translates into differences in species composition and ecosystem function.

A key point of interpretation is that the assessment of "impact" depends on the reference status and policy objective. Complete removal is most compatible with the restoration of a sandy seabed system and creates conditions for the return of soft-bottom communities, but simultaneously leads to the disappearance of a now-functional hard-substrate community. This is more than a discussion about species diversity, it involves changes in ecosystem processes such as filtration, secondary production, and local food web structure. Decommissioning therefore represents a clear trade-off between restoring pre-installation conditions and removing habitat that may have acquired ecological functions in the meantime, for example, as foraging or shelter habitat for demersal fish.

11.6 Indirect and Cumulative

Chapter 9, Indirect and Cumulative Effects, clarifies that the ecological consequences of decommissioning cannot be fully understood by focusing only on direct local effects. Indirect effects arise because decommissioning alters habitat structure and ecosystem processes, allowing effects to cascade beyond the direct footprint via food webs, sediment processes, and spatial use. The key insight is that decommissioning is not a simple "reset." While complete removal can restore the physical preconditions for soft-bottom habitat recovery, the direction and rate of ecological recovery are uncertain and depend on disturbance intensity, hydrodynamics, recolonization sources, and the background pressure in the area. This makes decommissioning a system transition with uncertain paths rather than a clear-cut return to a previous state.

Furthermore, the chapter demonstrates that post-decommissioning use also determines how the system develops. When decommissioning is accompanied by the reinstatement of bottom-disturbing fishing in areas, the combined effect of habitat loss and renewed fishing pressure can be ecologically more significant than removal alone. This mechanism is often less explicitly considered in practice but can be definitive for the ultimate ecological outcome. At the same time, complete removal prevents the spread of non-indigenous species associated with OWFs, although the magnitude of this benefit has not yet been sufficiently quantified.

Cumulative impacts pose a significant challenge in the North Sea. OWFs can reach the end of their lifespan within similar timeframes, but decommissioning can also coincide with the construction of other OWFs. Simultaneously, many other activities are taking place in the North Sea, such as oil and gas extraction, seismic surveys, shipping, maintenance of existing infrastructure, and the installation or removal of cables for both energy and telecommunications purposes. Cumulative impacts arise not only when similar activities occur simultaneously, but especially when similar pressures, such as underwater noise, seabed disturbance, or increased shipping intensity, accumulate over time and space. This shifts the relevant assessment scale from the individual project to the North Sea scale. The ultimate ecological impact depends primarily on how activities overlap in time and space, and not only on the effects of a single project.

The chapter demonstrates that adaptive management during decommissioning has its limitations in practice. Monitoring can provide valuable knowledge and help improve the planning of future projects, but during an ongoing decommissioning process, it is often difficult to implement adjustments. This is due to fixed schedules, safety requirements, and technical dependencies between activities. Adaptive management is therefore particularly important as a learning process between projects, with the first decommissioning projects being used to gain insight into ecological responses, recovery processes, and cumulative effects. In view of the larger wave of decommissioning in the coming decades, it is important to explicitly utilize these learning experiences.

11.7 Baseline

A key finding from this study is that uncertainties surrounding decommissioning largely results from a lack of data, particularly regarding the state of ecosystems immediately prior to decommissioning and the subsequent recovery pathways. A baseline is lacking. Monitoring programs often end or are scaled down in the later operational phase, while this period is important for understanding fully developed reef communities and establishing an ecological reference situation.

To reduce uncertainty, several priorities for monitoring can be identified. First, the ecological status of the OWF should be documented immediately prior to decommissioning, including the species composition, biomass, age structure, and functional characteristics of benthic communities on both the foundations and the scour protection. Second, the use of the area by higher trophic levels such as fish, seabirds, and marine mammals should be assessed, with particular attention to potential nurseries, feeding hotspots, and seasonal concentrations. Third, spatial and temporal patterns of avoidance and recolonization should be quantified to understand whether habitat recovery occurs after removal and over what timescale.

In addition, monitoring should explicitly consider scale: distinguishing between local effects at the turbine level, effects at the scale of OWFs, and potential impacts at the population or regional level. This includes improved data on species connectivity, distribution, and the cumulative interaction with other activities in the North Sea.

Monitoring, knowledge development, and establishing a robust baseline can thus play a supporting role in reducing uncertainty and improving future assessments. However, such monitoring should not be used to retroactively legitimize alternative decommissioning scenarios before clear policy decisions have been made regarding long-term ecological objectives.

11.8 KEC

The decommissioning of OWFs represents a relatively new and poorly documented phase in the lifecycle of offshore energy infrastructure. Unlike the construction and operational phases, knowledge about the ecological effects of decommissioning is scarce. Consequently, impact assessments are largely based on analogies with the oil and gas sector, model-based assumptions, and extrapolations of existing data, leading to uncertainties regarding the magnitude of the impact, spatial extent, and recovery processes. This uncertainty is exacerbated by the ongoing development of decommissioning techniques and by policy ambiguity regarding the required degree of removal, for example, with regard to scour protection and cables. The main uncertainties can be divided into knowledge uncertainty (ecological processes and recovery), technical uncertainty (implementation and disturbance intensity), and scenario and scale uncertainty (choice of removal option, timing, and cumulative overlap).

The KEC framework allows these uncertainties to be explicitly addressed, provided that it is transparently documented which effects are substantiated and which are based on modeling or expert judgment. Given the limited knowledge base, it is advisable to work with margins and worst case scenarios within the KEC rather than only with point estimates. This is particularly relevant for cumulative impact assessments, where simultaneous decommissioning, new OWF construction, and other North Sea activities can overlap spatially and temporally. Using average values in such situations can lead to a structural underestimation of the total ecological pressure.

Monitoring and adaptive learning can help gradually reduce uncertainties, but should be embedded in the existing permitting and policy framework. Because decommissioning conditions are often determined decades in advance, the value of monitoring lies primarily in strengthening system-level knowledge and improving future KEC analyses and policy choices. Integrating decommissioning into future KEC assessments therefore requires a more process-oriented and lifecycle approach, in which uncertainties are made explicit and cumulative dynamics at the North Sea scale are systematically incorporated.

12. Recommendations

The decommissioning of OWFs constitutes an ecologically relevant transitional phase within the lifecycle of offshore wind energy. While the operational phase is characterized by long-term, relatively stable effects, decommissioning is accompanied by short-term but often intense disruptions, such as increased shipping traffic, underwater noise, seabed disturbance, and disturbance from light and human activity. The nature and extent of these effects are largely determined by the chosen decommissioning strategy, the techniques used, the timing of implementation, and the extent to which decommissioning occurs at the same time with other activities in the North Sea. This context-dependent nature makes it necessary to explicitly and systematically incorporate decommissioning into ecological assessments and policy choices.

Long-term vision for the North Sea

A first recommendation is to develop a long-term ecological vision for the Dutch North Sea that includes the decommissioning of OWFs. It is essential to clarify which long-term nature goals are being pursued and which ecological changes are considered desirable or acceptable. Decommissioning raises fundamental questions about "winners and losers" in the ecosystem: some species and communities benefit from the development of hard substrate and reef structures during the operational phase, while others benefit from the restoration of dynamic soft-substrate conditions. Without an explicit vision, it remains unclear whether decommissioning should be viewed as restoration to a perceived original situation or as a conscious choice to maintain or further develop newly created natural values. This consideration requires a time perspective that extends beyond conventional policy and permitting periods, as ecological recovery processes often span decades.

Decommissioning policy

In line with this, it is desirable to further clarify the policy regarding complete removal and the handling of scour protection. Scour protection is ecologically key, as it often contains well-developed hard-substrate communities. At the same time, its removal can contribute to the restoration of natural seabed processes and habitat types. Clear criteria are needed to determine when retention or partial removal is ecologically and politically acceptable, and how responsibilities for abandoned structures, including monitoring and liability, are secured. Without such clarity, there is a risk of uncoordinated decision-making and inconsistent ecological assessments between projects.

Mitigation hierarchy

For the planning and implementation of decommissioning activities, it is recommended that the mitigation hierarchy will be explicitly applied as a guiding principle. This means that the primary focus should be on avoiding ecological impacts, for example, by scheduling work outside ecologically sensitive periods and preventing the simultaneous construction/decommissioning of nearby OWFs. When impacts cannot be completely avoided, the emphasis should be on minimizing the duration, intensity, and spatial extent of disturbance. Only when this proves to be insufficient should mitigative measures and, as a final step, compensation be considered. Such a systematic approach contributes to transparent and reproducible ecological assessments.

Ecological baseline

A key requirement for both assessment and mitigation is establishing an ecological baseline prior to decommissioning. Without a well-documented baseline, it is difficult to attribute observed changes to decommissioning activities rather than to natural variation or other pressures. In practice, monitoring efforts are often reduced or discontinued several years after the construction phase, once the mandatory operational monitoring has been met. Furthermore, in many cases, only limited or no long-term ecological monitoring was conducted prior to the construction phase. As a result, a well-documented baseline of the original situation is often lacking. Combined with the phasing out of monitoring during the operational phase, long-term developments are not structurally recorded, meaning that by the time decommissioning takes place, there is often no robust ecological baseline available.

Therefore, it is recommended to conduct targeted measurements several years prior to the start of decommissioning, focusing on both benthic communities on and around foundations and scour protection, as well as on surrounding soft-substrate habitats. This baseline forms the basis for impact assessment, mitigation options, and restoration evaluation.

Monitoring and recovery

Furthermore, it is important not to limit monitoring to the decommissioning phase itself, but to continue it in subsequent years. The ecological relevance of decommissioning lies not only in the immediate disruption, but primarily in the rate and direction of recovery. Long-term monitoring allows us to determine whether areas return to a previous state, reach a new equilibrium, or remain affected in the long term.

The length of the operational phase likely affects recovery dynamics. OWFs that have been present for decades may support established reef communities and altered food webs. Removing these mature systems can result in different recovery pathways than those seen in less developed systems. Understanding how operational lifespan influences post-decommissioning recovery is essential for interpreting ecological outcomes.

Decommissioning in KEC

For the further development of KEC assessments, it is recommended that decommissioning is explicitly included as a separate phase, with clear assumptions regarding implementation techniques, seasonality, and duration. Given the uncertainties surrounding future decommissioning practices, it is wise to consider at least one worst-case scenario, for example, with maximum noise production, seabed disturbance, and shipping intensity during an ecologically unfavorable period. By also considering alternative scenarios, such as complete versus partial removal, insight can be gained into the sensitivity of various ecological components. This approach strengthens the robustness of KEC assessments without abandoning the existing policy framework.

Cumulative effects

Cumulative effects deserve special attention. In the coming decades, several OWFs will reach the end of their lifespan in a relatively short time, while new OWFs are being built or existing ones are being repowered. Decommissioning may therefore coincide with other large-scale offshore activities, increasing the risk of ecologically relevant cumulative effects. It is therefore advisable that KEC and EIA processes consider the overlap of activities not only project-specifically, but also regionally and temporally.

Knowledge development

Finally, it is recommended to stimulate targeted knowledge development around a limited number of decision knowledge gaps. In particular, the ecological consequences of removing or maintaining scour protection, the recovery pathways of soft-substrate habitats after complete removal, and the thresholds for cumulative effects will determine future policy choices. The first large-scale decommissioning projects in the Dutch North Sea offer a unique opportunity to gather this knowledge. By systematically linking monitoring and evaluation to policy and assessment, decommissioning can be viewed not only as an end point but also as a learning phase that contributes to more sustainable and ecologically sound choices for the further development of offshore wind energy.

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Annexes

I: Roadmap Offshore Wind Energy 21 GW