Background Document on Nature-Friendly Decommissioning of Offshore Energy Infrastructure

Offshore Wind, Grid Infrastructure and Offshore Platforms

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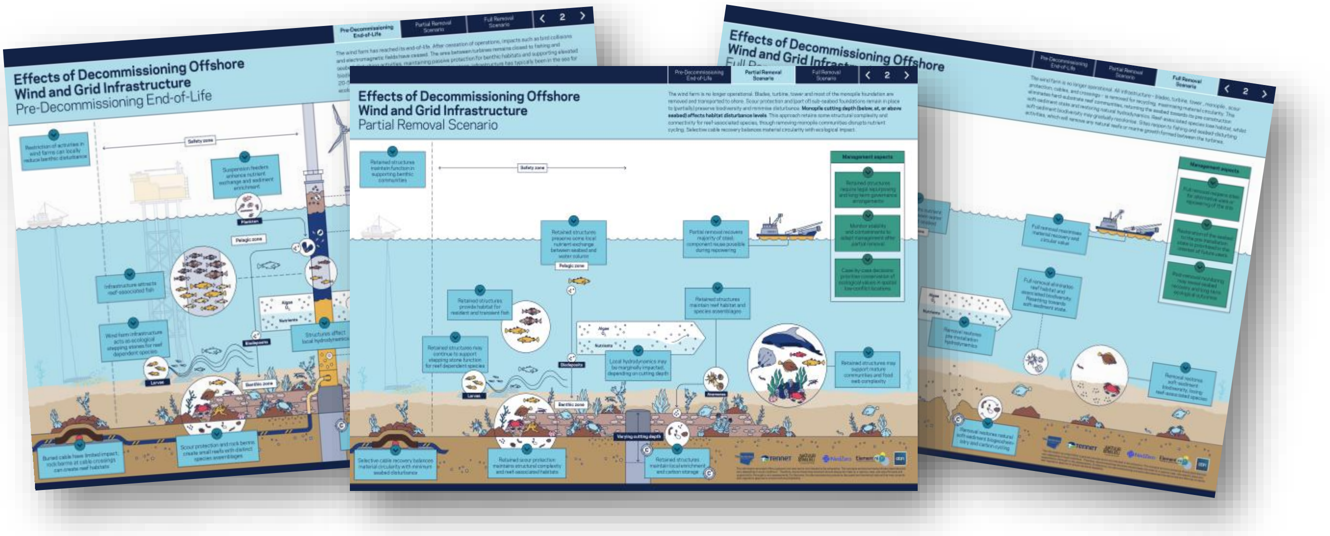

Background to the Nature-friendly Decommissioning Infographics

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Authors

Anne-Mette Jørgensen[1], Pim Somers[2], Valentijn Elsman[2], Jef Pattyn[2], Eva Maus[2]

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2: The North Sea Foundation | Stichting De Noordzee

Contact

The North Sea Foundation: info@noordzee.nl; +31 (0) 30 234 0016

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Summary and disclaimer

As the offshore energy sector continues to expand and mature, an increasing number of offshore structures will reach the end of their operational lifetimes in the coming decades. As these installations transition from active use to decommissioning, governments, operators and environmental stakeholders face a growing set of complex decisions. Decommissioning is no longer a purely technical task; it has become an ecological, regulatory and societal balancing act shaped by shifting baselines, evolving policy frameworks and expanding knowledge of marine ecosystems and the ecological functions of offshore structures within them.

This document covers the pre-decommissioning stage and the two decommissioning scenarios - full removal and partial removal - presented in the infographics for offshore wind turbines and offshore platforms in more depth. It first describes what we know about the ecological state of structures prior to decommissioning, providing context for understanding how different measures may affect existing ecological communities. It then outlines the ecological, technical and regulatory considerations that could shape each scenario.

The aim of this background document is not to prescribe a single preferred pathway. Instead, we try to frame the complexity of the choices ahead and emphasise that responsible decommissioning requires adaptive, evidence-based and context-dependent decisions.

So far, the partial removal scenario discussed is a theoretical option that does not yet have regulatory approval in the Dutch North Sea for wind farms (including sub-stations) and nowhere in the OSPAR region for oil and gas installations. For offshore wind, none of the scenarios have proven their technical feasibility in a real-world situation, nor have the impacts of decommissioning been monitored in practice. Where technically feasible, decommissioning approaches should aim to remove as much of the monopile as possible without disturbing the scour protection layer, in order to maximise material recovery while retaining ecological value at the seabed. For platforms, full removal as well as partial removal have been implemented all around the world, but generally without proper monitoring of the ecological effects of different decommissioning options. Hence, we primarily describe ecological effects of decommissioning scenarios (in the Southern North Sea) in terms of loss of the ‘new nature’ that has developed on and around the structures in question. In doing so, we strongly recommend that studies are set up to better understand the actual impacts of various decommissioning options, before it is too late. With current full-removal policies, we risk throwing out the baby with the bathwater.

This infographic has been developed as part of the Dutch Nature-friendly Decommissioning Project. This is a collaboration between environmental NGOs (the North Sea Foundation, Natuur & Milieu), EBN (the Dutch state participant in subsurface activities), NedZero (Dutch wind association), TenneT (TSO) and ElementNL (Dutch oil & gas association). The aim of the project is to explore how to create policy-space to permanently leave nature-enhancing man-made structures (artificial reefs and components of offshore wind farms and oil & gas platforms) in place in the Dutch part of the North Sea for the benefit of underwater biodiversity. Based on clear ecological standards and requirements and without creating a precedent that would undermine the general principle of full removal of disused offshore installations.

Offshore Wind & Grid Infrastructure

Pre-decommissioning end-of-life state

Definition

A wind turbine generator (WTG) in an offshore wind farm (OWF) consists of rotor blades supported by a hub. The hub is connected to the nacelle, which contains the gearbox and the generator, which converted mechanical energy to electrical energy. This structure is placed upon a tower standing on a foundation. Foundations may take different forms (monopile, gravity-based, tripod or jacket), of which the monopile is the most common type and the only type used in the Dutch North Sea. Surrounding the monopile is a scour protection layer consisting of natural rocks and/or artificial rocklike objects. Via cables, electricity is transported to an electrical substation (which in most cases has a jacket foundation that resembles that of an oil and gas installation) and from there further on to shore.

The cable network connects turbines to each other and to the substation platform, and from there to shore. Most export cables, (in the Dutch context) usually installed by TenneT, are buried about one meter deep into the stable seabed, while inter-array cables operated within the wind farm (installed by OWF developer) show variable burial depths depending on sediment type. In both cases, cables usually remain buried, except at crossing points where they are protected by rock berms. At these locations cables cross pre-existing cables or pipelines. On average the rock berm at a cable crossing (installed by TenneT) covers an area of ~0.2 Ha. Before 2032, 90 new cable crossings will be installed by TenneT (Hermans et al., 2025), which will cover a larger area.

As an Offshore Wind Farm (OWF) reaches its end-of-life, we believe that various decommissioning strategies should be carefully considered. Sound decision-making should be preceded by thorough monitoring of in the OWF site's current environmental state, establishing a 'pre-decommissioning' baseline as the reference point. This is particularly crucial given the lack of an evidence base on the effects of large-scale offshore wind infrastructure removal. During the pre-decommissioning end-of-life state of a wind turbine, it has ceased power generation but still remains physically intact. The operational impacts, such as bird collisions and electromagnetic fields are no longer present. On the other hand, the monopile continues to impact the mixing of stratified waters and the ecological communities that have developed on scour protection, turbine foundation and between turbines are still intact.

Before a wind turbine is decommissioned, the infrastructure has typically been in the sea for 20-30 years. During this period, the hard substrate of the tower and foundation (monopile), scour protection layer, cable crossings and electrical substation has come to function as an artificial reef. Although the cable crossings and electrical substations serve different purposes, it is expected that their impact and reef functions are similar to that of the scour protection layer and of oil and gas platforms with a similar jacket structure.

Within the wind farm and around electrical substations, only certain types of co-use of space are allowed under strict conditions. Active fishing is currently not allowed within Dutch wind farms and shipping is allowed only in specified corridors (unless it concerns maintenance ships for the wind farm). This means that ecological communities on the seabed between the turbines also develops in a different way than those outside the wind farm.

Reef formation & succession and biodiversity & species richness

When a monopile is placed into the mostly sandy seafloor of the Southern North Sea, it immediately adds vertical hard substrate, which develops into an artificial reef. Within months, the steel is covered by algae, hydroids, anemones, barnacles, mussels (*Mytilus edulis)* and amphipods (Coolen et al., 2022). The scour protection layer offers refuge, hydrodynamic shelter, and foraging opportunities (Glarou et al., 2020; Kingma et al., 2024, Ter Hofstede et al., 2022).

A five-year study in the Southern North Sea indicated that within the first year of the installation of the foundation, a clear vertical zonation of fouling species establishes. The upper zone hosts barnacles, algae and mussels with amphipods (Coolen et al., 2022). The marine splash midge (*Telmatogeton japonicus*) dominates the splash zone, the barnacle (*Semibalanus balanoides*) the high intertidal zone and the blue mussel (*Mytilus edulis*) the intertidal–shallow subtidal zone (De Mesel et al., 2015).

Deeper subtidal zones are dominated by communities of tube-building amphipods (*Jassa herdmani*), hydroids (*Tubularia* spp.), and anemones (Actiniaria) (De Mesel et al., 2015). A dominant genus of anemones is *Metredium* (Coolen et al., 2022) which also occurs in high abundances on hard substrates in the Borkum Reef area (Bos et al., 2025). Overall, mussels are the most biomass-dominant species, and amphipods the most numerous (Mavraki et al., 2020-a).

Because the construction of monopiles introduces new hard substrate, it may also play a role as stepping stone in the establishment and expansion of some non-indigenous species (Coolen et al., 2020-a, De Mesel et al., 2015). As of yet, the ecological risk and effect of the non-indigenous species found on monopiles is considered to be small to negligible (Dauvin, 2024). The possibility of an effect as a result of future upscaling is present.

Long-term studies in the Southern North Sea show that the biofouling communities on wind turbines are taxonomically and functionally different from the surrounding soft-sediment fauna. Therefore, introducing a vertical structure, can lead to higher local biomass and a shift in energy flow from sediment-based to water-column (Degraer et al., 2020; Coolen et al., 2020-a). It has been demonstrated that natural (geogenic) reef habitats appear to sustain greater biodiversity and host functionally different assemblages than artificial structures (OWF foundations and SPL without NID). This suggests that natural rocky reefs may exhibit higher functional resilience under environmental disturbance (Mavraki et al., 2026).

Colonisation occurs rapidly, but communities have not yet reached a stable climax state within the timescales studied so far (11 years) (Zupan et al., 2023). The duration over which this climax state occurs or if it will ever occur in the Southern North Sea remains uncertain. Succession, on the other hand, is clearly visible: pioneer assemblages dominate during the first two years, followed by increasing species richness and structure over the next few years. After a decade, turnover continues rather than forming a stable end state (Degraer et al., 2020; Zupan et al., 2023). So far, depth and season explain variation between communities more than age (number of years since construction) (De Mesel et al., 2015).

Over time, the accumulation of biodeposits and shell debris (Biofouling drop -offs) also results in a finer sediment grain size in the area immediately surrounding the structures (Lefaible, et al., 2023). Demersal species, such as flatfish, crustaceans and other bottom dwelling species benefit from the increased biodeposit input and organically enriched sediments (De Borger et al., 2025).

Benthic pelagic coupling

Filter-feeding species on the monopile intercept organic particles from the water and export them as faeces and pseudofaeces to the seabed. This process drives benthic–pelagic coupling, i.e. the exchange of food, nutrients and energy between the seabed and the water column. In doing so, nutrient cycling changes and enhances organic enrichment in the soft sediments surrounding the base (Degraer et al., 2020; De Borger et al., 2021).

Fish aggregation and food webs

As mentioned before, the associated structure of a monopile host diverse reef-associated communities. Besides the previously mentioned species, fish also respond to these new habitats in varying ways. For example, before distribution shifts as a result of climate change, Atlantic cod would show patterns of aggregation around turbine foundations and scour protection rocks. Here, they would feed on fouling-associated prey, and in winter, both adults and juveniles have been observed, suggesting that these sites may serve as spawning habitats (Reubens et al., 2014; Mavraki et al., 2021; Gimpel et al., 2023; Wilber et al., 2022). Pouting and black sea bass also feed heavily on reef-associated prey near monopiles (Reubens et al., 2011; Carey et al., 2020). While offshore structures clearly provide habitats that attract fish, several questions remain actively debated:

- Do they enhance local fish biomass production or only attract fish from elsewhere?
- Do they function as a breeding or nursery ground with higher growth or survival rates?
- To what extent do they contribute to increased population levels?
  (Glarou et al., 2020).

Artificial reef effects could, in principle, create ecological traps if they attract species into suboptimal or risky conditions (e.g., increased predation, altered prey availability, or contaminant exposure), leading individuals to invest energy in habitats that do not improve survival or reproduction. For mobile species such as Atlantic cod, it is unlikely that wind farms act as true ecological traps, since fish can move to alternative feeding or spawning grounds when conditions are suboptimal (Reubens et al., 2013). To date, empirical studies report no evidence that offshore wind farms function as ecological traps for fish, although long-term behavioural monitoring remains important (Bergström et al., 2013; Reubens et al., 2013). The concept remains relevant mainly as a precautionary framing: structures could attract individuals to areas where prey dynamics, noise exposure, or fishing pressure outside park boundaries reduce overall fitness, and decommissioning may raise the additional question of whether site-attached individuals can readily relocate once the artificial habitat is removed.

Habitat complexity & design / Cable infrastructure

Around the base of each turbine, the scour protection layer (SPL) stabilises the sediment, but also creates a small rocky reef. Similar structures are also present at some cable crossings, where protective rock cover provides comparable hard substrate for colonisation.

Studies consistently state to find higher epibenthic abundance and different species composition on SPLs in comparison to sand. Diversity indices are not always higher, but communities are consistently distinct and enriched in reef-associated taxa (e.g., crabs, lobsters, hard-substrate fishes and sessile epifauna), especially when complex designs are used (Ter Hofstede et al., 2022; Zupan et al., 2024; Spielman et al., 2023).

The gaps between rocks provide shelter and rough surfaces that are favoured by lobsters, small demersal fish, and many invertebrates (Hofstede et al., 2022; Zupan et al., 2024). Additionally, there is a variety of food sources that can accumulate between the stones of the SPL's, attracting more species to feed there (Mavraki et al., 2020-b). The same is expected at cable crossings (Hermans et al., 2025). These rock berms function as artificial reefs and are colonised by similar fouling organisms as monopiles and SPLs, providing microhabitats for invertebrates and small demersal fish (Hermans et al., 2025).

Small-scale complexity of the material is crucial for species richness (Lengkeek et al., 2017; Van Duren et al., 2016. Experimental setting: Kingma et al., 2024). Varied stone sizes and crevices increase the number of available microhabitats and ecological functions (Langhamer et al., 2012), and surface complexity promotes the colonisation by marine fauna and flora (Perkol-Finkel & Sella, 2014).

The composition of communities is driven by an interplay of environmental and site-specific nuances. On one hand, factors such as depth, season, abiotic factors and structure design are suggested to be the strongest drivers of community composition (Coolen et al., 2022; Langhamer, 2012; Zupan et al., 2024). On the other hand, based on observations from a study by Zupan et al. (2023) community composition can still be different at sites sharing similar characteristics. Elements such as priority effects, timing of species arrival and biological interactions could also have an effect (Scheffer, 2020; Stroud et al. 2024). Currently, empirical data and knowledge are lacking on the effects of environmental factors influencing benthic communities in OWFs (Li et al., 2023). Based on this it can be concluded that community composition is highly case dependent and widely discussed.

Sediment biogeochemistry and carbon

Even though the monopile, SPL and cable crossing mainly serve as reef-like elements, the surrounding soft sediment also changes as a result of the presence of the wind farm. Suspension feeders release biodeposits that settle nearby and increase organic inputs to the seabed. Studies from North Sea wind farms show changes in sediment biogeochemistry and macrofauna consistent with organic enrichment and the spread of ecosystem-engineering species such as tube-builders (Coates et al., 2014; De Borger et al., 2021).

A study in the Belgium North Sea shows that the effects on the soft sediment between the turbines is affected in a 5–50-kilometer radius around a monopile. Within this radius higher organic matter and changes in grainsize is measured (De Borger et al., 2021). Changes in sediment composition around offshore wind turbines reflect a combined physical–biological process. Lefaible et al. (2023) describe how altered flow and resuspension patterns near foundations can affect local granulometry, while biofouling communities dominated by suspension feeders contribute organic enrichment through deposition, and “biofouling drop-offs” (shell debris and fallen organisms) add additional material to adjacent soft sediments. Together, these mechanisms can increase the fine fraction and promote locally finer sediments close to the structures (Lefaible et al., 2023).

Hydrodynamics & stratification

Monopile foundations of offshore wind turbines interact with tidal currents and generate turbulent wakes that modify local hydrodynamics and enhance vertical mixing in the water column. This wake-driven turbulence can significantly reduce vertical gradients in temperature and salinity, resulting in a more homogeneous water column and a local decrease in stratification (Hendriks et al., 2025). Observations show that these effects are typically spatially confined to the immediate wake region (on the order of tens to hundreds of metres downstream of a monopile) but are clearly measurable and dynamically significant.

The enhanced mixing associated with monopiles influences sediment resuspension, seabed shear stress, and the transport of nutrients, oxygen, and particulate matter, thereby affecting key biogeochemical processes. At the scale of a single monopile, the resulting disturbance to stratification is relatively limited but detectable, with studies showing localised increases in mixing and partial erosion of stratification within the wake. However, when aggregated across an entire offshore wind farm, these effects can become more extensive (Schultze et al., 2020). Numerical modelling suggests that the cumulative turbulence generated by multiple foundations can alter current velocities and stratification patterns at regional scales, with changes on the order of ~10%, comparable to natural interannual variability (Christiansen et al., 2023).

Changes in hydrodynamics and stratification can propagate through the ecosystem via bottom-up processes. Enhanced mixing can alter the vertical distribution and fluxes of nutrients and suspended sediments, thereby influencing light availability and primary production, with potential consequences for higher trophic levels. Scenario studies indicate that large-scale offshore wind development in the North Sea may lead to measurable changes in suspended particulate matter dynamics and primary productivity, although effects may vary regionally and partly offset each other depending on local conditions (Zijl et al., 2023).

Overall, the ecological implications of monopile-induced mixing depend strongly on site-specific hydrography, stratification strength, and seasonal variability. While small-scale impacts around individual turbines are generally limited in extent, their cumulative effects across large wind farm arrays—and especially under future large-scale expansion scenarios—may play a significant role in shaping regional hydrodynamics and ecosystem functioning. Nonetheless, uncertainties remain regarding the magnitude and persistence of these impacts, highlighting the need for further integrated field observations and modelling efforts.

Refuge and exclusion effects

During the operational state, fishing, particularly bottom trawling, is generally prohibited within turbine arrays for safety reasons. This restriction also provides passive protection to benthic habitats and the species living around monopiles and scour protection. Over time, these no-trawl zones allow longer-lived species to re-establish, increase habitat complexity, and support higher biodiversity and biomass (Knorrn et al., 2024; Lindeboom et al., 2011)

When examining individual species groups, studies found that wind farm areas tend to host higher quantities of polychaetes, echinoderms and demersal fish compared to surrounding reference areas. These patterns indicate that offshore wind farms contribute to a strong reef effect, providing shelter and food supplies while functioning as no-take zones. Consequently, they can act as local biodiversity hotspots, potentially facilitating spill-over effects to nearby areas for certain species groups (Knorrn et al., 2024).

Decommissioning scenarios

Definition: Partial or Full removal scenarios

When the wind farm permit expires (on average after 30-40 years under current regulations), it may be feasible to extend the lifetime of the wind farm further or to repower it. Life-time extension depends on the integrity of the structures and the economic and technical feasibility of maintaining the wind turbines. Repowering may imply that parts of a turbine are reused but could also imply that the existing wind farm is decommissioned and a new one constructed in the same place. If life-time extension or partial reuse are unfeasible or not allowed for, decommissioning is the next step.

In theory, decommissioning may entail full removal to shore, partial removal to shore or partial removal to another location, being a new wind farm or a dedicated reefing location. In the Netherlands and many other North Sea countries, full removal to shore is currently a legal obligation, unless the operator proves that it is technically unfeasible to do so in a safe manner. However, currently discussions are ongoing within OSPAR aiming to formulate a joint policy for decommissioning of renewables. Within this discussion, partial removal is also considered as an option that could be allowed in some cases.

In our view, the decommissioning decision should carefully be based on the following considerations:

- The balance between ecological benefits of structure retention, e.g. in relation to nature conservation and restoration goals,
- the impact of leaving parts of structures in place on safety,
- the interests of other known (potential) users,
- and the impact of recyclable material being lost.
- the CO_2 footprint (emissions e.g. vessels; removing carbon sequestrating structures e.g. reefs) and sustainability implications of decommissioning options.

Proper decision making hence requires solid monitoring of ecological values developing on and around offshore wind installations over time and adaptive, case-by-case assessments taking into account topical local and regional effects of full vs. partial removal.

For evaluating ecological trade-offs, baseline conditions are generally recognised as important factors. They provide a point of comparison for assessing ecological change and potential restoration outcomes.

However, climate change makes the applicability of such baselines after 40+ years increasingly uncertain. Shifting baselines, such as rising sea temperatures, could alter ecosystem functioning to such an extent that original baseline conditions are no longer realistic or achievable. Moreover, opinions differ on whether the pre-construction condition should be considered as preferable to or more natural than the post-construction condition, considering the fact that the pre-construction condition would often be strongly impacted by decades of bottom-trawling and/or other forms of disturbing human activities.

Full removal scenario

In the Dutch North Sea, full removal to shore implies that ALL elements of a wind farm are removed and transported to shore, incl. the entire foundation/monopile (which may have been driven some 30-50m into the seabed), scour protection, cables and cable crossings and electrical substations. Onshore, everything is recycled and/or handled in line with national waste handling regulations.

Patial removal scenario

A partial removal implies that rotor blades with hub, nacelle, gearbox, generator and tower (top part of the monopile) are removed and transported to shore. The monopile foundation might be cut off below, at or above seabed level, giving different levels of disturbance to the surrounding habitat. The part above the seabed will be removed and transported to shore. A further partial removal scenario is that the entire monopile is removed, while the scour protection is left in situ. This may be a relevant option given current technological and cost constraints and may also be of ecological interest because hard substrate near the seabed is retained while the circular value of steel is completely retrieved. However, this scenario would require further technological innovation.

Cables will also be removed unless this has a severe impact on ecological values that have developed on the cable crossings (case by case dependant). Scour protection, cable crossings and maybe the footings of electrical substations are left in situ. This decision is based on balancing the interests and safety of other users of the sea and the ecological value associated with the various components.

All removed parts are then transported to shore for onshore recycling in line with national waste handling regulations (EU: Waste Framework Directive, 2008/98/EC).

If parts of a wind farm are left in place (i.e. partial removal), it is necessary to ensure that this is clearly marked on maps, and maybe in situ indicated with buoys and/or navigation lights in order to minimize the risk of accidents.

In order to protect the remaining hard substrate/nature after partial removal, it may be necessary to keep the area closed for various seabed-disturbing activities. Where structures are retained, arrangements have to be made regarding long-term governance, liability and continued monitoring responsibilities.

Partial removal scenario

Partial removal: Reef formation & succession / Biodiversity & species richness

If the monopile is cut at or a few meters below the seabed while leaving deeper parts and the scour protection layer (SPL) in place, direct disturbance to established epifauna is reduced and parts of the reef-based ecosystem can be retained. From a biodiversity perspective, partial removal may preserve ecological functions that have developed over time—similar to patterns reported for "topped" oil and gas installations (Lemasson & Knights, 2026). The remaining SPL can continue to provide structural heterogeneity and shelter for reef-associated species, thereby supporting foraging habitat, local nutrient cycling in nearby sediments, and some level of benthic–pelagic coupling. However, removing monopile-dwelling species (e.g., mussels and amphipods) may disrupt established interactions and nutrient pathways, which could also affect communities living on or within the retained SPL.

Whether retained structures develop into mature, diverse, trophically complex assemblages depends on surface area and structural complexity, species interactions (competition and facilitation), and environmental conditions (depth, location, hydrodynamics, organic input) (Mavraki et al., 2020-b; Ter Hofstede et al., 2022; Zupan et al., 2023, 2024). At the same time, what constitutes a "mature" reef and when (or if) a climax state occurs in the context of monopiles, and SPLs remains uncertain (see Chp. *Pre-Decommissioning End-of-life state: Reef formation & succession and biodiversity & species richness*). Although retained foundations may be colonised by species such as the plumose anemone (*Metridium senile*), high species richness and trophic complexity may remain limited due to space competition and relatively small available area (Zupan et al., 2023).

Environmental conditions further constrain the persistence of reef-like functions, particularly sediment dynamics. In highly dynamic seabeds, hard substrate may become buried by sand, potentially eliminating reef function unless sediments are stabilised (e.g., by flume/tube worm reefs) (Naylor & Viles, 2000). Because some material remains in place, impacts on established reef fauna may be less immediate; field studies suggest partial retention can preserve up to ~80% of benthic and reef-associated communities compared to near-complete loss after full removal (Fortune et al., 2020). Nonetheless, this outcome is debatable if key monopile-associated taxa are removed while the SPL is retained, because those taxa may have been integral to nutrient cycling and benthic–pelagic coupling within the broader reef system. Finally, even if functions are maintained, the resulting assemblage remains distinct from the historical baseline prior to structure installation.

Partial removal: Connectivity & spatial dynamics

As described above, partial removal allows some of the previously mentioned benthic community and connectivity functions to remain (see Chp. *Partial removal: Reef formation & succession / Biodiversity & species richness*). Retained hard substrates maintain corridors for native and non-native species dispersal, although this may require ongoing biosecurity management to monitor and potentially limit the spread of invasive species that may form harmful threats.

However, studies show that non-indigenous species primarily occur on the intertidal zone of monopiles (Coolen et al., 2020-b; De Mesel et al., 2015), which would be removed with partial decommissioning (Li et al., 2023).

Partial removal: Sediment biogeochemistry & carbon / Refuge & exclusion effects / Hydrodynamics & stratification

By limiting excavation and sediment resuspension, partial removal also reduces the previously mentioned carbon loss and minimises biogeochemical disturbance, maintaining part of the newly developed benthic ecosystem. Again, the theoretical consideration about the species that are removed from the monopile and their associated effects on the rest of the ecosystem, should be taken into account.

If safety zones are kept in place, retained structures can continue to act as partial refuges for marine life by preventing trawling disturbance.

Hydrodynamic effects mostly disappear once above-seabed structures are removed, although some limited turbulence and sediment mixing may persist immediately around remaining foundations.

Partial removal: Materials, circularity and waste handling

Partial removal requires careful management of potential chemical emissions from residual materials. Steel from monopiles left in place is lost for recycling, but reuse or repurposing of substructures (e.g. J-tube cable protection or support structures for sacrificial anodes) can reduce waste and maintain habitat value. In case of repowering at the same location, existing components such as scour protection and possibly other foundation elements can be reused on site, reducing the need for new materials and minimising additional seabed disturbance.

With partial removal, steel from monopiles and sections of cable infrastructure may be lost for recycling. This can indirectly increase demand for raw materials and lead to higher impacts from mining activities elsewhere in the world. The scour protection layer is also lost for recycling, although its circularity value is generally low. If recovered, the rocks first need to be cleaned of marine growth, which would then have to be handled as waste onshore. Such operations require large handling capacity and can generate considerable odour nuisance locally. Leaving the SPL in place offshore reduces these onshore waste handling impacts.

Leave-in-place (buried, stable) options impose the lowest disturbance, avoiding long trenching, sediment plumes and high CO2 emissions. For cables specifically, selective recovery strategies, which remove only exposed cables while keeping buried sections intact, balances risk reduction with minimal seabed disturbance.

Full removal scenario

Full removal: Hydrodynamics & stratification

When monopiles and other structures are removed at the end of life, several ecological processes change immediately. Turbine wakes, which previously enhanced local mixing, disappear once the above-seabed parts of the structures are gone. Stratification returns, but ecological consequences remain uncertain. Decommissioning assessments consistently flag this as a process that ceases when turbines are removed. (Schultze et al., 2020, Christiansen et al., 2023).

Full removal: Reef formation & succession / Sediment biogeochemistry & carbon / Pollution & material legacy

Full removal erases the entire hard-substrate community that has developed on monopiles and SPL. It cuts off the supply of biodeposits from suspension feeders and ends the mixing effect that had developed over time. The seabed thus returns to its pre wind farm construction state (Fowler et al., 2018).

Physically, full removal involves excavation, cutting, and recovery of the SPL and cables. These operations resuspend fine sediment and organic matter, creating plumes that can spread to surrounding areas, depending on current speed and timing. If multiple sites would be decommissioned simultaneously, particularly in the case of electrical substations within or in proximity to OWFs, these plumes could accumulate and impact larger areas.

Under current regulations in the Dutch North Sea, after full removal, the wind farm area would reopen for bottom-trawling and other seabed-disturbing uses, with all associated ecological consequences.

Full removal: Connectivity & spatial dynamics

Based on the observations made in chapter *Partial removal: Connectivity & spatial dynamics*. Removing all structures would eliminate the stepping stone pathway functions of monopiles for both native and non-indigenous species. While this may help limit further spread of non-indigenous species, it would also eliminate connectivity corridors that supported recovery and gene flow among native reef-associated species.

Full removal: Refuge & exclusion effects

Once a wind farm is removed and safety zones are lifted, the site typically reopens to fishing. Probably, bottom-trawling quickly resumes, reintroducing physical disturbance to the seabed. The loss of this passive protection may nullify decades of ecological recovery and complexity of the (sandy) seabed which may have taken place during the no-trawl period.

Full removal: Cable infrastructure

At decommissioning, complete removal of export cables also requires re-excavating long stretches of sediment. This creates turbidity, potentially disturbing buried fauna or releasing stored organic carbon. With current techniques, the footprint of such work can be extensive, especially where cable routes extend for tens of kilometres.

Offshore Platforms

Pre-decommissioning end-of-life state

Definition

A platform consists of a topside positioned on a deck above the water and a steel jacket under water with footings into the seabed or an under-water concrete foundation. Around the foundation and area's where the cables or pipelines exit the seabed onto the platform, sometimes rocks or concrete 'mattrasses' have been placed to protect the footings from scour.

During the operational state, electrical substations in the Dutch North Sea are platforms that collect electricity generated by the wind turbines and step-up the voltage for efficient transmission to shore with minimal losses. Usually, substations are located within or close to an OWF. They are structured with transformers, switchgear and high voltage export cables, mounted on a jacket foundation, similar to that of an oil and gas platform (from here on O&G installation).

Because of their similarity in structure under water, effects on the marine environment of the structure itself are expected to be the same for O&G installations and electrical substations. Both will be referred to as platforms, unless otherwise stated.

The hard substrate of the platforms, rock dump, mattrasses and cable crossings function as an artificial reef (Ponti, 2002; Whomersley & Picken, 2003). The top side of the platform may function as a mini-island being used by birds for resting, nesting and foraging (Ronconi et al., 2014).

Environmental effects on/of substations in comparison to O&G platforms may arise due to the fact that electrical substations are located close to or within OWFs, where effects could potentially interplay between electrical substations and monopiles.

O&G installations in particular, are sometimes manned. The manned installations generally are substantially larger than the unmanned installations and need to be accessible for helicopters. Underneath the installation, wells have been drilled kilometres deep into the seabed to the reservoir(s) from which the oil or gas were extracted. These wells are either still connected to the platform with pipelines or have been used for exploration only and later plugged and abandoned.

Reef formation and succession

When a platform is installed in the North Sea, it introduces a three-dimensional structure into a largely soft-sediment environment. The steel jacket and footings provide extensive vertical and horizontal hard surfaces that behave as a relatively complex artificial reef. These structures are colonised by dense biofouling communities including mussels, anemones, hydroids, sponges, and barnacles, forming a multi layered habitat (Van Der Stap et al., 2016; Fortfeath et al., 1982; Whomersley & Picken, 2003). Again, a vertical zonation occurs along the jacket structure (Schutter et al., 2019; INSITE, 2024).

Overall, this creates a community that is taxonomically and functionally different from the surrounding seabed communities due to the lack of hard substrate in the Dutch North Sea (Coolen et al., 2020-b; INSITE, 2024). Like older wind farms, existing platforms were not designed with nature-inclusive principles in mind, but in some cases happen to offer good conditions for colonisation by various hard-substrate dependent species. Over time, succession may lead from early colonisers such as barnacles and tube-building worms to more structurally complex assemblages dominated by suspension feeders such as mussels (*Mytilus edulis*) and anemones (*Metridium dianthus*).

The rough surfaces, beams and cross-braces of jacket structures provide numerous microhabitats, allowing both sessile and mobile species to occupy different niches. Compared to wind turbine monopiles, platforms with a jacket foundation are larger and structurally much more complex, often supporting greater biodiversity and biomass per unit area (Lemasson et al., 2024).

Benthic pelagic coupling

The ecological influence of platforms extends beyond their physical footprint. Filter-feeding organisms intercept suspended particles and export faeces and pseudofaeces to the seabed, driving benthic-pelagic coupling and nutrient cycling beneath and around the platforms. These biodeposits stimulate microbial activity and enrich nearby sediments. These support detritivores and benthic invertebrates that feed higher trophic levels (Fowler et al., 2020). The jacket structures also create vertical gradients of light, water flow and food availability, resulting in strong zonation patterns from the surface to the seabed. In the upper layers, algal growth is common, while deeper sections are dominated by filter feeders and detritivores adapted to lower light and higher sedimentation (INSITE, 2024; Mavraki et al., 2025).

Biodiversity & species richness / Fish aggregation & food webs

Fish communities respond strongly to these new habitats. Numerous studies show high densities of fish aggregating around O&G installations, where they feed on invertebrate prey and smaller fish sheltering within the fouling layers (Fortune et al., 2024).

Observations of spawning and juvenile stages near platform bases suggest that, similar to wind turbines, these structures function not only as attraction sites but, in some cases also as breeding grounds and nursery habitats (Todd et al., 2018). The steel framework offers refuge from predators, hydrodynamic shelter and foraging opportunities. In deeper sections, flatfish, crustaceans and demersal species benefit from the increased detrital input, sediments enriched by organic matter (Buyse et al., 2023). Although sources on electrical substations are lacking in comparison to O&G platforms, the same effects are expected due to the similarity in structure.

Refuge & exclusion effects

A 500-metre operational safety zone around platforms prohibit all activities unrelated to the platform, including but not limited to fishing and bottom-disturbing activities. This effectively creates temporary marine refuges.

These exclusion zones may allow fish to stay out of the nets of fishermen, benthic habitats to recover and long-lived species to re-establish. Potentially this could lead to higher biodiversity and biomass compared to surrounding areas outside the safety zone.

Arguably, in comparison to wind farms, where this exclusion zone covers many square kilometres, the platform’s exclusion zone could be negligible. Empirical studies directly assessing seabed recovery and biodiversity within the 500 m exclusion zones are scarce and remains a research gap. Scientific evidence around no-trawl effects due to offshore structures are in this case provided indirectly through wind farms and marine protected areas (Leewis & Klink, 2022).

Connectivity & spatial dynamics

Literature states that connectivity between O&G installations strengthens regional ecological networks (Coolen et al., 2020-a) and international networks (Henry et al., 2018), allowing especially epifaunal species with pelagic larval stages of several weeks to spread much further than they would normally be able to (Henry et al., 2018; Coolen et al. 2020 -a). Larval exchange and adult dispersal between structures enable gene flow and population stability for both native and non-indigenous species. The installations thus serve as stepping stones across the otherwise sandy North Sea, linking populations that would otherwise remain isolated (NSITE Phase 2 report; Henry et al., 2018). The same is expected for electrical substations due to similar structures and for rock dumps at cable crossings (Hermans et al., 2024).

Decommissioning scenarios

Definition: Partial or Full removal scenarios

When an offshore wind farm reaches the end-of-life phase and is being decommissioned, electrical substations usually undergo the same process, as they are considered part of the wind farm. For O&G platforms the end-of-life phase is reached, when it is no longer economically feasible to continue extracting oil or gas from the reservoir below the platform. Unless the platform can be reused for another legitimate purpose (e.g. CO_{2}- or H_2-storage for O&G installations) it has to be decommissioned.

This process is logistically complex and takes place in several phases, meaning that the full decommissioning process for a platform usually takes 5-10 years from the start of planning for decommissioning to the moment that the jacket has been removed and all wells safely plugged & abandoned. In theory, decommissioning may entail full removal to shore, partial removal to shore or partial removal to a special reefing location. In the North Sea, full removal to shore is the standard solution for all types of platforms. For electrical substations the regulatory framework in the Dutch North Sea is derived from the *'Wet windenergie op zee'.* For O&G installations this is agreed under OSPAR Decision 98/3 and reflected in national regulations, including the Dutch Mining Act (*Mijnbouwwet*).

Derogations may be granted for concrete gravity-based structures and steel jackets weighing more than 10,000 tons and constructed before 1998. Partial removal/leaving certain elements in place may be considered where full removal is technically unfeasible or unsafe (OSPAR Decision 98/3, Annex 1). Partial removal might be allowed for if it entails repurposing or reuse of parts of a structure for nature conservation or restoration purposes supported by national authorities.

At the moment partial removal is not allowed in the Netherlands. In case of O&G installations, reuse is limited to the topside of an installation for a new O&G installation or for reservoirs and sometimes platforms and/or pipelines for CO2-storage. Regulations regarding the decommissioning of pipelines is left to the national authorities. In the Netherlands operators can apply for a derogation. If accepted by the Dutch Ministry of Economic Affairs, pipelines can be left in place in a manner that ensures they are safely over trawlable and cleaned according to agreed procedures.

Full removal scenario

In the Dutch North Sea, full removal to shore implies that the topside and jacket will be removed and transported to shore, together with cables. Footings are cut at 6 m under the seabed, removed and transported to shore. For O&G installations, wells are safely plugged and abandoned before the installation is removed. Pipelines and natural rock dump may be left in place with permission from the Ministry of Economic Affairs. Onshore, everything is recycled and/or handled in line with national waste handling regulations.

Partial removal scenario

With partial removal the topside and parts of the jacket will be removed and transported to shore, together with any cables. Clean footings, rock dump, matrasses and possibly the lower part of the jacket are left in situ, preferably ensuring 25m free draught (safe navigational depth) above the remaining structures.

Again, the decision on which components of a platform are left in situ has to be based on balancing the (safety) interests of other users of the sea and the ecological value of the various components. The removed parts are brought onshore where everything is recycled and/or handled in line with national waste handling regulations. For O&G installations, wells are safely plugged and abandoned before the platform is removed.

Partial removal scenario

Partial removal: Reef formation & succession / Biodiversity & species richness

When a platform is decommissioned, it might be considered to leave parts of the platform in place (>25m) below sealevel. Typically, a small part of the jacket and footings would be cut somewhere above the seabed. The cutting depth is based on case-by-case considerations, especially taking into account navigational safety.

This approach could retain parts of the ecological function of the artificial reef while reducing the environmental footprint of removal. By cutting the structure at a safe navigational depth (>25m clearance above; IMO, 1989), much of the established biofouling community, as well as the benthic enrichment processes, could remain intact (Lemasson & Knights, 2026). Partial removal therefore preserves some of the complex reef habitat that has developed over decades and maintains the trophic linkages between the structure, surrounding sediments, and pelagic species (Fortune et al., 2020). Modelling and field data indicate that up to 80% of the reef-associated communities may be retained under such scenarios compared to near-total loss following full removal (Fortune et al., 2020), depending on the height of the structure left in place. In case of partial removal, the pre-construction state (before structure placement) of the ecosystem hence is *not* restored.

Partial removal: Sediment biogeochemistry & carbon / Hydrodynamics & local mixing

Leaving parts of the structure in place reduces direct physical disturbance to benthic communities and avoids sediment plumes caused by cutting and lifting from under the seabed. The remaining hard substrate continues to support sessile organisms, which in turn sustain higher trophic levels. Furthermore, by maintaining sections of the structure, carbon storage in surrounding enriched sediments is disturbed less severely. Sediment resuspension is limited, and the microbial processes responsible for carbon burial remain active.

However, the magnitude and spatial extent of these effects differ from those at OWFs. Whereas OWFs cover a much larger and closely connected area, effects at platforms occur at the level of an individual structure or a cluster of ecologically interconnected structures. Thus, the potential consequences of any sort of removal are likely to be more pronounced in an OWF context.

Partial removal: Materials, circularity and waste handling

Partial removal may reduce energy use, vessel time, and emissions compared to complete removal, depending on the size of the platform and level of complexity of removal. In the Dutch part of the North Sea, most platform jackets are small enough to be removed in a single lift, which means that it is not expected that partial removal will lead to significant reductions of emissions or cost. Leaving part of a steel jacket offshore implies a loss of valuable material for recycling. This effect must be considered in decision-making, balancing ecological benefits against lost circularity value.

Partial removal: Refuge & exclusion effects / Connectivity & spatial dynamics

From an ecological perspective, the residual structure may continue to act as a refuge and spawning ground for fish such as cod, saithe and pouting and provides stepping-stone habitats for invertebrates and sessile fauna. The partial structure also retains elements of the passive protection effect if the 500m safety zone is maintained. Connectivity between nearby structures remains at least partly intact, sustaining larval dispersal and gene flow among reef-associated species (Henry et al., 2018; Coolen et al., 2020-a,c). However, this same connectivity may also support the persistence or spread of non-indigenous species. For that reason, biosecurity during cutting and transport, cleaning and containment of fouled elements, remains essential regardless of the decommissioning approach.

Partial removal: Governance, monitoring & ecological legacy

When parts of a structure, specifically O&G installations, are left in place, these would have to be (legally) repurposed into a formal artificial reef and arrangements made regarding long-term liability and responsibility for monitoring and management of the reef. ‘Rigs-to-reefs’ programmes, already implemented in other regions, especially in the US, provide valuable learnings in terms of potential for further enhancing the ecological values of such artificial reefs as well as regarding long-term governance and liability (see review by: Lemasson & Knights, 2026). This could potentially also be the case for electrical substations. The ecological effectiveness of partial removal depends on careful site selection, structural stability and long-term monitoring to ensure that retained sections continue to function as productive and diverse habitats.

Full removal scenario

Full removal: Sediment biogeochemistry & carbon / Hydrodynamics & local mixing

Complete removal represents the most disruptive form of decommissioning and has the highest immediate environmental footprint. Full removal requires cutting the jacket below the seabed, lifting massive structures to the surface, and transporting them to shore for dismantling and recycling (Lemasson & Knights, 2026; Sommer et al., 2018). The seabed thus returns to the pre-platform construction state.

This process temporally produces substantial noise and vibration, heavy vessel traffic and sediment plumes (Fernandez-Betelu et al., 2024; Sommer et al., 2018).

Sediment resuspension can temporarily reintroduce fine particles and organic matter into the water column, increasing turbidity and locally reducing oxygen levels, with the duration of these disturbances varying from hours to weeks depending on sediment type, hydrodynamic conditions, and the removal technique used.

Where platforms have been in place for decades, these sediments may contain accumulated bio deposits and enriched carbon stocks. Removing the structure disturbs these layers and can release stored carbon back into the water, potentially offsetting years-to-decades of accumulation. Although each individual site contributes modestly, the cumulative effect of widespread full removals could be ecologically and climatically significant across the North Sea (Fowler et al., 2020).

Full removal: Reef formation & succession / Benthic–pelagic coupling

Once the structure is removed, the entire hard-substrate community disappears. This eliminates tonnes of sessile biomass and all associated fauna, resetting the site to its pre-construction soft-sediment state. Benthic-pelagic coupling stops, and the area loses its artificial reef function entirely. Fish that had used the structure for foraging, spawning, or shelter either relocate or are lost from the local population. Studies show rapid declines in local fish densities following removal of reef-like structures, with biomass and diversity decreasing substantially (Fortune et al., 2024). Studies concerning the effects of a full removal scenario are lacking (Lemasson & Knights, 2026), but a study by Bomkamp et al. (2004) in California, states these processes cease when a O&G installation is fully removed.

Up for discussion, these impacts may, to a small extent, be mitigated if rock dumps remain in place, which can continue to provide habitat and support partial ecological functions. Although, this is on a small scale due to the small amount of rock dump present around platforms – in the Dutch sector of the North Sea, most platforms do not even have rock dump around them.

Full removal: Pollution & material legacy / Well closure & cuttings piles

Pollution risks in the Dutch North Sea context due to decommissioning are generally limited.

Modern decommissioning standards are designed to minimise environmental release during structure removal.

Specifically in the case of O&G installations, wells are subject to plugging and abandonment requirements (P&A) designed to prevent leakage irrespective of the selected decommissioning scenario (full or partial removal). Additionally, operators are subject to a statutory duty of care (nazorgplicht) under the Dutch Mining Act, further mitigating risks.

In the Dutch sector, cuttings piles and sediments containing legacy materials of platforms, are generally not considered an issue in decommissioning – in previous studies of the seabed around platforms where pollutants were present in the past, these have been shown to have declined to near-background concentrations.

Full removal: Refuge & exclusion effects

Full removal also ends decades of passive protection from bottom-trawling. Once exclusion zones are lifted, fishing vessels can re-enter previously closed areas. This reintroduces bottom disturbance and further increases mortality for benthic organisms that had recolonised and stabilised during the operational state. The loss of protection can rapidly reduce biodiversity and biomass (Fortune et al., 2020).

Again, magnitude and spatial relevance should be taken into account. The exclusion zone (500 metres) covers a much smaller area in comparison to windfarms, covering tens to hundreds of square kilometres.

Full removal: Connectivity & spatial dynamics

Connectivity between platforms and other structures is also lost after full removal. Native species lose their stepping-stone corridors, which can fragment populations and reduce regional genetic exchange. While this may reduce the spread of some invasive species, the net effect is often negative also for native reef-associated biodiversity (Henry et al., 2018; Coolen et al., 2020-c).

In broader context, the role of artificial hard substrate structures in the Dutch North Sea is evolving (Coolen et al., 2020-b). Historically, O&G installations held an important share of artificial hard substrate, specifically in the north and central North Sea, where natural rocky habitats are scarce (Derived from: Martins et al., 2023; Van Duren et al., 2016). Over the next 6 years, 2600 wells, 12 million tons of topsides, and >130,000 tons of subsea infrastructure are scheduled for decommissioning (Lemasson & Knights, 2026). However, with the rapid expansion of offshore wind farms, including electrical substations, the overall amount of artificial substrate in the region is increasing substantially (Krone et al., 2012). While the ecological importance of oil and gas structures as hard substrate sources is declining at local scale, they still provide valuable reef-like habitat in deeper and northern areas where wind development remains limited (Derived from: Martins et al., 2023).

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