



Challenges and Innovation Pathways for Eco-friendly Decommissioning of Offshore Wind Farms in the Dutch North Sea

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Executive summary

Offshore wind farm decommissioning is an emerging challenge characterised by increasing volumes, limited large-scale experience, and evolving regulatory frameworks. This report identifies key challenges and priority innovation pathways for environmentally responsible decommissioning and end-of-life (EoL) management of offshore wind farms (OWFs) in the Dutch North Sea. The study was commissioned by RVO and TKI Offshore Energy in anticipation of increasing decommissioning volumes where practical experience remains limited.

The analysis combines a desk study with insights from an expert and stakeholder workshop involving 32 participants from industry, research institutes, and government. Innovation areas have been qualitatively prioritised against cost reduction potential, environmental footprint, circularity, technical and regulatory readiness, and Dutch industry potential.

Key findings

- **Regulatory and evidence gaps** create significant uncertainty in the selection of decommissioning strategies (e.g. full versus partial removal), increasing project risk and cost. Consistent assessment methods and mechanisms for knowledge sharing are currently lacking.
- **Foundations (monopiles):** full-removal concepts (e.g. vibro-extraction, hydraulic overpressure) show strong potential but require validation at scale. Cutting-based approaches are more mature but typically result in greater ecosystem disturbance and lower circularity performance.
- **Scour protection:** conventional recovery methods are technically mature but slow, costly, and disruptive for the local ecosystem. The cost and complexity of similar operations are often underestimated. EoL decisions require balancing cost, circularity potential, and the ecological value that may develop on scour protection over time.
- **Inter-array cables (IAC):** removal by pulling is often preferred due to lower costs, although burial depth, seabed conditions, and crossings may introduce operational and environmental constraints. Handling and pre-processing remain labour-intensive and could benefit from specialised solutions.
- **EoL processing and capacity:** ports, vessels, and downstream processing facilities (particularly for blades, polymers, and permanent magnets) become bottlenecks as decommissioning volumes increase and overlap with installation activities.
- **Limited opportunities for large-scale demonstration** constrain the market uptake of promising technologies, slowing technology maturation and potentially undermining the feasibility of full removal strategies for early decommissioning projects.

Key recommendations

- **Launch a coordinated innovation and demonstration programme** on early Dutch decommissioning sites to mature removal and processing technologies, with risk/cost sharing and open dissemination of data and lessons learned.

- **Strengthen tender and permitting incentives** for ecology, environmental footprint reduction and circular EoL, supported by measurable criteria and consistent methods (e.g., LCA and monitoring protocols).
- **Target subsidy instruments** to (i) advance technologies across TRL levels, (ii) quantify ecological and life-cycle impacts, and (iii) accelerate Re-X (Reuse, Repower, Refurbish, Recycle) value chains and port/processing infrastructure, ideally coordinated with other North Sea countries.

Abbreviations

Abbreviation	Description
EIA	Environmental Impact Assessment
EoL	End-of-Life
eDNA	Environmental DNA Monitoring
IAC	Inter Array Cable
IMO	International Marine Organization
JUV	Jack Up Vessel
KEC	Kader Ecologie en Cumulatie (Framework for Assessing Ecological and Cumulative Effects)
LCA	Life Cycle Assessment
LCoE	Levelised Cost of Energy
MP	Monopile Pile foundation
O&G	Oil and Gas
OSS	Offshore Sub Station
OSPAR	Oslo and Paris Conventions
OWF	Offshore Wind Farm
Re-X	Reuse, Repower, Refurbish, Recycle
ROV	Remotely Operated Vehicle
TP	Transition Piece
TRL	Technology Readiness Level
UNCLOS	Convention on the Law of the Sea
WTG	Wind Turbine Generator
XLPE	Cross-linked polyethylene

1 Introduction

1.1 Background

The Netherlands has rapidly expanded its offshore wind capacity to meet national climate and energy targets. As a result, a growing number of offshore wind farms are expected to reach the end of their operational lifetime in the coming decade. This will introduce substantial technical, logistical, environmental, and regulatory challenges related to the decommissioning of offshore wind assets.

At present, experience with offshore wind decommissioning at scale remains limited. As a result, there is no clear consensus on the most suitable technical approaches, end-of-life (EoL) pathways, and removal strategies. The implications of key choices such as full versus partial removal, recycling routes, and decommissioning methods are not yet fully understood in terms of ecological impact, circularity, cost, logistics, permitting, and grid implications. Moreover, alignment across stakeholders on these aspects is still evolving.

Against this background, Rijksdienst voor Ondernemend Nederland (RVO) and TKI Offshore Energy commissioned this study. The objective is to assess the current state of the art, identify key challenges, and explore promising solution pathways for offshore wind farm decommissioning. The study considered technical, logistical, ecological, regulatory, and financial dimensions, with a particular focus on identifying priority areas for innovation and knowledge development. In addition, it also examined in which areas Dutch companies and research organizations are well-positioned to contribute. The results are intended to support the prioritisation of innovation efforts and to inform future policy and innovation programme development within TKI Offshore Energy.

1.2 Objective and research questions

This report aims to identify and structure the main innovation needs for decommissioning of offshore wind farms in the Dutch North Sea. The study has been guided by the following research questions and needs formulated by the client:

1. What is the state of the art regarding decommissioning technology (both with and without full removal of foundations and cables) and the anticipated impact on ecology?
2. Analyse the challenges for decommissioning of offshore windfarms, both with a view to improving circularity and to the business case of offshore windfarms.
3. What are the technical and logistic challenges and possibilities for eco-friendly decommissioning?
4. What are the possibilities and challenges for "eco-friendly decommissioning by design". How can this be stimulated?
5. Suggest solution pathways for all the challenges mentioned above
6. Provide suggestions for required knowledge developments, regulatory development and technical innovations for these pathways. These should be analysed including regulatory, technical and financial aspects and prioritized.

7. In what fields of expertise in this domain do Dutch enterprises and/or research institutes have (or can they get) the best position?

To address these points the presents a review of current practices and technologies combined with stakeholder input from a workshop and a qualitative prioritization of innovation areas.

1.3 Scope and boundaries

This study focuses on offshore wind farms in the Dutch North Sea and is scoped primarily to bottom-fixed wind farms with a monopile foundation, which is the dominant foundation type in the Dutch context.

The analysis considers the main offshore wind farm subsystems and decommissioning-related activities:

- wind turbines,
- monopile foundations and associated transition-piece-related removal issues,
- inter-array cables,
- scour protection, and
- offshore logistics, onshore handling, and end-of-life processing.

The scope of the study, outlined in Figure 1.1, also included offshore substations (OSS), and the structured workshop output contains a few meaningful OSS-related points across operations, reuse, ecology, and governance themes. However, the detailed analysis and prioritization are centred on the core subsystems above due to their higher impact on key performance metrics per MW installed.

The study does not aim to provide a fully exhaustive inventory of all decommissioning technologies, contractors, or commercial offerings. Likewise, it does not constitute a project-specific engineering study or permitting strategy for any individual wind farm. The focus is instead on identifying recurring challenges, innovation pathways, and areas where further demonstration, evidence development, or policy clarification may be valuable.

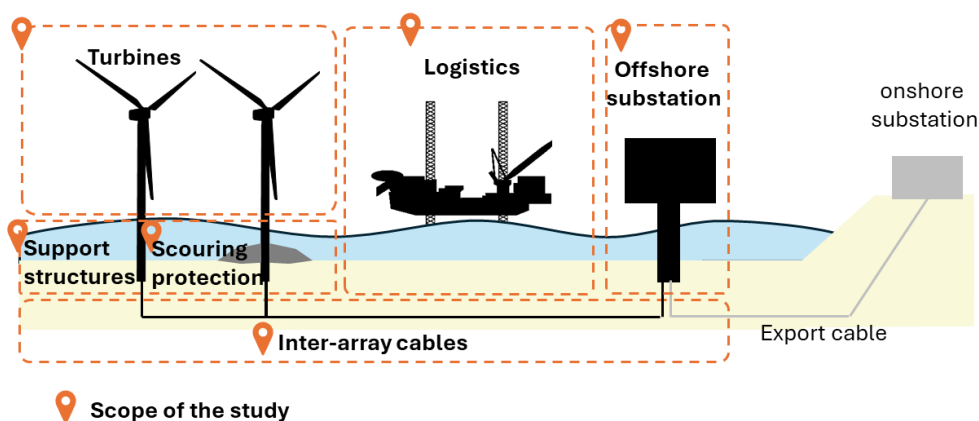


Figure 1.1 Scope of the study: Wind turbines, support structures, inter-array cables, scour protection, OSS and logistics.

1.4 Report structure

The report is structured to move from context, to evidence, to innovation priorities, and finally to conclusions and recommendations. This structure guides the reader from understanding the current decommissioning context, through the evidence base, to the identification and prioritization of innovation areas.

Chapter 2 explains the approach used in this study, including the desk study, the expert and stakeholder workshop, the way evidence is interpreted, and the prioritisation method. Chapter 3 then provides concise baseline context on current decommissioning practices and constraints for the main subsystems. Chapter 4 identifies the main innovation areas and solution pathways emerging from the desk study and workshop. Chapter 5 presents the prioritisation of these innovation areas. Finally, Chapters 6 and 7 provide the overall conclusions and recommendations for RVO, TKI Offshore Energy and the wider Dutch offshore wind ecosystem.

2 Methodology and approach



2.1 Desk study

The desk study provides contextual foundation for this report. It is based on a review of scientific literature, technical reports, commercial solutions, and ongoing research and development initiatives, supplemented by TNO internal expertise and selected expert input.

Given the limited and evolving experience with offshore wind decommissioning, the desk study should be interpreted as a structured overview of recurring challenges and solution directions, rather than as a complete inventory of technologies or suppliers. Examples included in this report are used illustratively and do not imply completeness or endorsement of specific parties or technologies.

2.2 Expert and stakeholder workshop

An expert and stakeholder workshop was organised by TNO on 7 April 2026 in Amsterdam to gather targeted input from across the decommissioning value chain and complement the findings of the desk study. The workshop brought together over 30 participants from industry, research, government and non-governmental organisations, including engineers, scientists, and managers. It aimed to capture practical experience, stakeholder perspectives, and perceived innovation needs in offshore wind farm decommissioning, guided by the central question:

What knowledge development and innovations best contribute to eco-friendly decommissioning of offshore wind farms?

The workshop was structured into three thematic domains:

1. Operations & logistics (vessels, sequencing, feasibility, cost drivers),
2. Legislation, monitoring & ecology,
3. Recycling & end-of-life (EoL).

Within these themes, discussions were organised across subsystems, including wind turbines, foundations, cables and scour protection. Offshore substations (OSS) were also discussed and are therefore reflected in the structured workshop outputs.

A structured qualitative approach was applied during the workshop:

- individual idea generation,
- discussion & clustering at table level,
- consolidation into challenge and solution statements.

The outputs were subsequently translated into structured entries, including subsystem, theme, type (challenge, solution, observation), and uncertainty level. Importantly, the workshop results should be interpreted as structured stakeholder inputs, not as validated facts or consensus conclusions.

Table 2.1 Expert & Stakeholder workshop schedule

Scheduled	Session	Breakout session
20 mins	Introduction and goal of the project	
50 mins	Session 1 - Operation & Logistics	1.1 - Wind turbine
		1.2 - Foundation
		1.3 - Cables & scour protection
15 mins	Plenary session & break	
50 mins	Session 2 - Legislation, Monitoring & Ecology	2.1 - Wind turbine
		2.2 - Foundation
		2.3 - Cables & scour protection
15 mins	Plenary session & break	
50 mins	Session 3 - Recycling & EoL	3.1 - Wind turbine
		3.2 - Foundation
		3.3 - Cables & scour protection
30 mins	Plenary session Wrap up & Closure	

2.3 Treatment of evidence

This report combines insights from literature and workshop input. As a result, not all findings have the same level of validation, and some reflect stakeholder perspectives rather than established practice. Where evidence is limited, the report focuses on identifying uncertainties, constraints, and potential directions, rather than making definitive comparisons or claims.

2.4 Prioritization method

Based on the desk study and workshop outcomes, identified solution pathways were grouped into innovation areas and assessed using a qualitative multi-criteria framework. Each innovation area was scored across six weighted criteria:

1. **cost reduction potential** (proposed weighting: 2.5),
2. **ecological footprint reduction potential** (proposed weighting: 2),
3. **circularity potential** (proposed weighting: 2),
4. **technical readiness** (proposed weighting: 0.5),
5. **regulatory readiness** (proposed weighting: 0.5),
6. **Dutch industry potential** (proposed weighting: 2.5).

Cost reduction and Dutch industry potential were assigned the highest weighting in the overall assessment, followed by ecological footprint reduction and circularity potential reflecting their importance for both project feasibility and innovation policy objectives. Regulatory and technical readiness were assigned lower weighting to reflect ongoing regulatory update efforts (e.g. within OSPAR) and the need to invest in promising innovation across the whole spectrum of technology readiness levels to prevent ruling out potentially disruptive innovation.

The scoring system is qualitative/semi-quantitative:

- it supports comparison between innovation areas,
- it does not imply precise numerical accuracy,
- outcomes should be interpreted as indicative rather than definitive rankings.

The prioritization is intended to support:

- identification of promising innovation directions,
- structuring of future programmes,
- discussion between stakeholders.

The full scoring logic and detailed tables are provided separately.

Table 2.2 Categories for the prioritization of decommissioning and EoL solutions

Category	High score (3)	Medium score (2)	Low score (1)
Cost reduction potential	Estimated potential reduction in decommissioning campaign costs compared to baseline: >5 k€/MW.	Estimated potential reduction in decommissioning campaign costs compared to baseline: 1-5 k€/MW.	Estimated potential reduction in decommissioning campaign costs compared to baseline: <1 k€/MW.
Ecological footprint	Significant reduction of local ecosystem disturbance and/or potential biodiversity	Moderate potential reduction of local ecosystem disturbance compared to	Negligible benefit and/or detrimental effects on local

reduction potential	enhancement compared to baseline.	baseline (e.g. by reducing large vessel operations at site) or reduction of overall environmental footprint of decommissioning campaigns (e.g. reduction of GHG emissions).	ecosystem and overall environmental impact compared to baseline.
Circularity impact	Large potential contribution to offshore wind farm circularity and value-retention compared to baseline (i.e. contributing to high-value recycling, repurposing, or reuse of large material quantities).	Moderate potential contribution to offshore wind farm circularity and value-retention compared to baseline (e.g. moderate value retention, or limited material quantities).	Negligible benefit (or detrimental effects) on offshore wind farm circularity compared to baseline.
Technical readiness	Estimated TRL level: > 7. Technology commercially proven in a relevant environment (e.g. offshore installation or oil & gas decommissioning). Limited upscaling and moderate adaptation may still be required.	Estimated TRL level: 6-7. Technology demonstrated in a relevant environment within innovation projects. Further development, upscaling, and validation under commercial conditions are required.	Estimated TRL level: ≤ 5. Technology not yet demonstrated in a relevant (offshore) environment.
Regulatory readiness	The target method/technology/approach complies with current regulatory frameworks, enabling prompt commercial implementation. Required permits and approvals are not expected to be an issue.	Partially defined or under developed regulatory frameworks pose risks towards the commercial applicability of the target method/technology/approach. Some adaptation of existing law, standards, or best practices would be required for that.	Significant uncertainty regarding regulatory compliance and/or acceptance by authorities.
Dutch industry potential	A large share of the value creation can be delivered by the Dutch industrial supply chain (e.g., core activities, services, manufacturing, execution).	A meaningful share of the work can be executed by Dutch industry, but key elements depend on non-Dutch suppliers and/or limited domestic capacity is currently available.	Limited to no involvement of the Dutch industrial supply chain; most work and value creation is expected to occur outside the Netherlands.

2.5 Limitations and uncertainties

This study is subject to several important limitations:

- **Limited real-world experience** - Large-scale offshore wind decommissioning, particularly for modern large monopiles, has not yet been widely executed, resulting in significant uncertainty.
- **Evolving regulatory context** - Regulatory frameworks, especially regarding partial removal and leave-in-place options, are still developing and may change in the coming years.
- **Illustrative desk study** - The desk study highlights representative technologies and approaches but does not aim to be exhaustive.
- **Workshop-based evidence** - Workshop outputs reflect stakeholder perspectives, which may differ or conflict, rather than validated or agreed conclusions.
- **Qualitative prioritization** - The prioritization relies on expert judgement and currently available information. The results should be interpreted as indicative comparisons rather than precise or objective rankings, and may change as new evidence emerges.

These limitations should be considered when interpreting the findings, particularly where conclusions relate to relatively immature technologies or policy-dependent decisions.

3 State-of-the-art practices and baseline context for decommissioning

This chapter provides a concise overview of current practices in offshore wind farm decommissioning, covering the main removal strategies, technical approaches, key challenges, and emerging solutions. The discussion is structured by subsystem, allowing for a focused analysis of system-specific considerations, while cross-cutting topics such as ecological impacts and regulatory frameworks are addressed in dedicated sections given their overarching relevance.

3.1 Foundations and transition pieces

3.1.1 State-of-the-art approaches and reference case

Monopile foundations are the dominant support structure for offshore wind farms in the Dutch North Sea. A typical foundation system consists of:

- the monopile (MP), which is driven into the seabed,
- the transition piece (TP), which connects the monopile to the tower,
- secondary steel, including boat landings, platforms, and access systems.

The connection between MP and TP is commonly grouted, although bolted connections are also used in newer designs, and some recent concepts adopt TP-less monopile configurations. This interface is particularly relevant for decommissioning, as it affects how the structure can be dismantled and lifted. From a decommissioning perspective, TP-less designs may reduce the need for a separate TP removal campaign, but they increase the total lift mass of the structure, placing higher demands on crane capacity.

At system level, two main decommissioning strategies can be distinguished for the monopile:

- **Partial removal** - where the monopile is cut below seabed level, the upper part (including transition piece) is removed, and the embedded section is left in place. The monopile is likely to be cut using abrasive waterjet or diamond wire cutting technology.
- **Full removal** - where the entire monopile is extracted from the seabed. To overcome the frictional forces, vibratory extraction and jetting-assisted methods will likely be used.

In practice, the choice between these approaches determines the overall decommissioning concept, including vessel (and crane) requirements, offshore/onshore operations, and interaction with other subsystems such as scour protection.

For the purpose of comparison in this report, partial removal by cutting 6 metres below seabed level is used as a reference case, consistently with a previous TNO study

recently commissioned by the Ministry of Climate and Green Growth [1]. This provides a consistent basis for evaluating alternative approaches and innovation pathways.

3.1.2 Key constraints and considerations

An important uncertainty is the interaction between the pile and the surrounding soil. After decades of operation, soil conditions may have changed due to consolidation and cyclic loading. These effects influence the forces required for extraction, which must overcome shaft friction along the pile, possible suction at the pile base, and the self-weight of the structure (including potential formation of soil plugs in the smaller diameter MPs [2]). These forces are difficult to predict accurately, particularly after long-term soil evolution.

Soil conditions play a key role in removal feasibility. In non-cohesive soils such as sands, vibration and fluidisation-based methods are generally more effective, whereas cohesive soils such as clays can significantly increase resistance and reduce the effectiveness of these approaches [2] [3].

Access to the removal location is another key constraint. For outer cutting-based approaches (e.g., Claxton Engineering external MP water jet cutting tool [4]), scour protection and seabed material may need to be removed to expose the monopile externally. Internal cutting methods avoid external dredging but require access inside the pile, which may be restricted by internal platforms and steelwork and may require some internal dredging and scour protection removal as well.

The transition piece connection introduces an additional challenge. Grouted connections are difficult to separate offshore and may require cutting above or below the interface, rather than direct removal of the grout, which is non-trivial. The presence of secondary steel can further complicate access and lifting operations and may require offshore dismantling to ensure accessibility, depending on the decommissioning strategy.

Monopile geometry is a key factor in removal feasibility. Modern monopiles are characterised by large diameters, which increase cutting lengths in partial removal scenarios and lead to higher frictional forces, thereby placing greater demands on lifting capacity and removal equipment.

From an operational perspective, heavy-lift vessel availability, lifting capacity, and campaign sequencing are key drivers of cost and risk. Monopile removal is not an isolated activity; it interacts strongly with the removal of the other subsystems and overall logistics planning.

From a circularity perspective, monopiles are predominantly made of high-value structural steel, which has a well-established recycling chain. However, recovery of intact or high-quality steel sections depend on the selected removal approach, as well as the ability to efficiently handle and pre-process the steel (e.g. cleaning, cutting) to ensure high rates of material recovery can be achieved.

3.1.3 Emerging solutions

Research and development around monopile foundations is mainly focused on full-extraction methods. While these concepts have been demonstrated in controlled or pilot environments, their performance at full scale, particularly for large-diameter monopiles and varying soil conditions, remains uncertain. The key bottleneck is the availability of full-scale testing and demonstration opportunities in representative conditions (e.g. featuring settled soil).

Some emerging solutions include:

- **Axial vibrations** - axial vibration applied to the monopile to reduce shaft friction by liquifying the surrounding soil. Example: VLT Tandem system [6], GIANT [5].
- **Torsional vibrations** – torsional vibrations to reduce shaft friction that can be complimented with axial vibrations. Example: VibroTwist [6]
- **Jetting-assisted extraction** - injection of water around or inside the pile to fluidise the soil and facilitate removal, often combined with vibrations. Example: Vibrojet® concept [7].
- **Hydraulic overpressure** - pressurising the inside of the monopile to generate an upward force, potentially reducing lifting requirements. This approach requires sealing of the pile and careful control of pressure levels to avoid structural or operational risks. Examples: HyPe-ST and DeCoMP [8] [9].

3.2 Inter-array and export cables

3.2.1 State-of-the-art approaches and reference case

Offshore wind farm electrical cables are typically buried below the seabed to protect them from external damage. Inter-array cables (IACs) are generally installed at burial depths of approximately 1-2 m, while export cables may be buried deeper, up to around 3-4 m depending on site conditions. Actual burial depth and cable position may change significantly over the farm operational lifetime (20-35 years) due to sediment transport, seabed mobility, and local hydrodynamic conditions.

From a system perspective, cable decommissioning strategies are primarily defined by the intended end-of-life (EoL) pathway and the feasibility of retrieval. In practice, four main approaches can be distinguished:

- **Full removal by pulling** - Direct extraction of the cable by applying pulling force from a vessel. This method is conceptually simple and widely applied, particularly in sandy seabeds where soil resistance is limited. However, it typically leads to significant mechanical damage of the cable, making it unsuitable for reuse and repurposing end-of-life routes.
- **Gentle removal by de-burial and retrieval** - Reverse installation approach where the cable is first exposed (e.g., using de-trenching or fluidisation tools), followed by controlled recovery. This preserves cable integrity and enables reuse or repurposing but requires expensive specialised vessels and equipment.
- **Partial removal** - Only particular sections are removed, while the remainder (e.g., landfalls or crossings) is left buried in situ.

- **Leave in situ** - The cable is de-energised and left in place entirely, where allowed by regulations.

In current practice, full removal by pulling is the dominant approach when removal is required. Operations are typically performed using offshore construction support vessels or multi-cat vessels, depending on required pull forces and deck space. Recovered cables are usually cut into manageable sections and sent for recycling, with material recovery focused on the conductive metals such as copper and aluminium.

For the purpose of comparison in this report, full removal by pulling is used as the reference case. This reflects current industry practice and provides a baseline against which alternative EoL pathways, including reuse-oriented concepts, can be evaluated.

3.2.2 Key constraints and considerations

A key uncertainty in cable decommissioning is the actual burial condition at end of life. Due to long-term seabed dynamics, cables may be deeper buried, partially exposed, or laterally displaced relative to their as-installed condition. This directly affects the required pull forces, feasibility of extraction, and selection of removal method.

Seabed conditions play a central role in determining removal feasibility. In non-cohesive soils such as sands, direct pulling or fluidisation-based de-burial is generally feasible. In contrast, cohesive soils or areas with complex stratigraphy can significantly increase resistance and complicate both extraction and pre-excavation activities.

The presence of cable crossings introduces additional operational constraints. Intersections with other cables or pipelines require careful handling and may necessitate local excavation or partial removal strategies to avoid damage to third-party infrastructure.

Environmental constraints are another important consideration. Cable extraction and especially de-burial activities can lead to sediment resuspension and increased turbidity, which may be restricted by permitting conditions. Controlled dredging is technically feasible but preferably avoided due to its high environmental impact.

From an operational perspective, uncertainty in burial depth and route position can complicate offshore operations and increase campaign duration. Accurate pre-decommissioning surveys are therefore critical to reduce risk and optimise removal strategies.

On-deck handling and processing also present practical challenges. Many offshore cables contain bitumen or other viscous compounds, which can complicate cutting, stripping, and material separation. These substances may adhere to tools and equipment, requiring specialised handling procedures and introducing additional personnel safety hazards and environmental risk mitigation measures.

From a circularity perspective, current practices are largely limited to material recycling. High-value pathways such as reuse or repurposing are constrained by the need for non-

destructive recovery methods. Emerging concepts, such as in-situ casing systems enabling low-damage extraction, may offer future opportunities to improve circularity, but are not yet widely applied in offshore wind farm IAC systems.

3.2.3 Emerging solutions

Research and development in cable decommissioning is primarily focused on enabling non-destructive recovery methods, with the aim of supporting higher-value end-of-life pathways such as reuse and repurposing. While several concepts are under development, most are not yet widely demonstrated at offshore wind farm scale and remain subject to technical, operational, and economic uncertainties.

Some emerging solutions include:

- **In-situ casing systems** - Concepts where a protective casing (e.g. steel pipe) is installed around the cable during installation. At end of life, the cable can be recovered by flushing water through the casing, reducing friction and enabling extraction without mechanical damage. Example: SOCCS concept [10].
- **Advanced fluidisation techniques** - Improved jetting or fluidisation methods aimed at more controlled and efficient de-burial, reducing sediment disturbance while enabling gentle cable recovery. These may include optimised nozzle configurations or liquidification of the soils using vibrations. Example: Frequensea [11].
- **Low-impact de-burial tools** - Development of trenching and excavation tools specifically designed to minimise environmental impact (e.g. turbidity and seabed disturbance) while maintaining sufficient production rates for offshore operations.
- **Integrated recovery and processing systems** – Optimized vessel solutions that combine cable recovery with onboard preprocessing (e.g. cleaning, stripping, separation), improving efficiency and reducing handling constraints. These systems may support different EoL pathways depending on recovery quality. Examples: Maasvliet vessel [12].
- **Design-for-decommissioning approaches** - Increasing attention is being given to cable system designs that explicitly consider end-of-life aspects, including material selection (e.g. reduced use of bitumen), modular cable concepts, and installation methods that facilitate later recovery.

3.3 Scour protection

3.3.1 State-of-the-art approaches and reference case

Scour protection is commonly installed around offshore wind turbine monopiles to prevent seabed erosion and maintain foundation stability. The conventional approach consists of a rock-dumped protection system, typically formed by a two-layer structure:

- **Filter layer** – smaller rocks to keep the seabed grains securely in place.
- **Armour layer** – larger rocks to resist direct hydrodynamic forces.

Alternative forms of scour protection that are used in other industries or applications, such as rock bags, concrete/geotextile mattresses, or integrated structural solutions, are not often used in offshore wind except for cable crossings.

Installation is generally performed using rock-dumping vessels, which place material around the monopile in a controlled manner. However, decommissioning of scour protection is not simply the reverse of installation, as the material is typically dispersed, partially buried, and interlocked with surrounding sediments, making controlled retrieval technically more challenging and less predictable than placement.

At end of life, current regulatory frameworks typically require removal of scour protection. In practice, this is most commonly performed using mechanical retrieval methods, such as rock grabs or clamshell buckets deployed from offshore vessels. These systems remove material in discrete batches and transport it to the surface for disposal or reuse.

For the purpose of comparison in this report, removal using a rock grab or clamshell bucket is taken as the reference case. This reflects current industry practice and provides a baseline for assessing alternative approaches.

3.3.2 Key constraints and considerations

A key challenge in scour protection removal is the inherently low operational efficiency of mechanical retrieval methods. Rock grab and clamshell operations are performed in discrete cycles and are highly dependent on weather conditions, resulting in long campaign durations and high operational costs.

Complete removal is difficult to achieve in practice. Residual rock material often remains on the seabed, particularly in areas that are difficult to access. This is especially relevant close to the monopile (if left in place), where tight tolerances and collision risks limit the effectiveness of retrieval equipment.

Seabed disturbance is another important consideration. Mechanical removal leads to sediment resuspension and redistribution, which may be constrained by environmental regulations. The extent of disturbance depends on soil conditions, rock size, and operational method.

Uncertainty in initial scour protection configuration and condition at end of life can further complicate removal. Over time, rock layers may have redistributed, settled, or partially embedded into the seabed, affecting removal efficiency and required effort.

From a circularity perspective, recovered rock material may be suitable for reuse; however, this depends on factors such as contamination, particle size distribution, and the efficiency of handling and transport operations. In addition, the handling and processing of scour protection materials introduce biohazard-related risks due to the extensive marine growth and biological communities that have colonised the hard substrate over time.

3.3.3 Emerging solutions

Research on scour protection in offshore wind is primarily directed towards improving ecological performance and reducing end-of-life removal requirements. Although removal costs are expected to be significant [1], this is not proportionally reflected in the level of research on efficient removal methods. This imbalance may be partly explained by regulatory uncertainty regarding whether, and under what conditions, scour protection has to be removed.

Nonetheless, several emerging solutions are being explored, including:

- **Nature-inclusive scour protection** - Scour protection designs incorporating ecological features, such as textured rock placement, artificial seagrass mattresses, or modular reef units, which promote habitat formation. These concepts may support leave-in-place strategies at end of life, although regulatory acceptance remains uncertain. Examples: Reef Cubes®, which are piloted at the RWE Rampion Offshore Wind Farm [13].
- **Reduced or no-rock scour protection** - Configurations with reduced rock volumes or complete omission of traditional armour layers. Examples: Luchterduinen explores the use of ecological structures or hybrid systems to achieve sufficient stability with lower material input [14].

3.4 Wind turbine generator

3.4.1 State-of-the-art approaches and reference case

Offshore wind turbines are typically decommissioned using a reversed installation sequence. The standard approach involves:

- removal of the blades from the rotor hub,
- lifting of the nacelle,
- and sequential removal of tower sections.

These operations are generally carried out using a jack-up vessel (JUV), which provides stable lifting conditions and sufficient crane capacity for component-wise dismantling.

Alternative lifting strategies have been considered, such as using large semi-submersible crane vessels to remove structures in a single lift [15], or lifting (part of) the rotor with the blades still attached. For early-generation offshore wind turbines, such concepts may reduce the number of offshore lifts, although practical application for installation remains limited due to technical complexity and reduced workability.

For the purpose of comparison in this report, conventional decommissioning based on reversed installation using a JUV is taken as the reference case. This reflects current industry practice and forms the baseline against which alternative lifting and processing strategies are evaluated.

Following offshore removal, turbine components are typically transported to port for further dismantling and processing. Offshore dismantling is minimised due to high costs, safety risks, and operational constraints.

3.4.2 Key constraints and considerations

A key driver in WTG decommissioning is the high cost and risk associated with offshore lifting operations. Weather windows, vessel availability, and crane capacity strongly influence campaign duration and overall project economics. Reducing offshore time and activities is therefore a key objective in alternative concepts.

Component size and mass present important constraints, particularly for modern turbines. Large rotor diameters and increasing nacelle weights place higher demands on lifting capacity, even for component-wise removal. This limits the feasibility of alternative strategies such as single-lift removal for newer turbine generations.

Handling and transport of large components require careful consideration. Efficient stacking, sea fastening, and port logistics are critical to avoid bottlenecks between offshore removal and onshore processing.

From an end-of-life perspective, reuse of complete offshore turbines is generally not expected. Components such as blades are designed for a specific lifetime under harsh conditions, and structural degradation limits their suitability for reuse. Selective reuse may be possible for smaller components or spare parts, but this is not considered a primary pathway, in contrast to onshore wind turbines.

Material composition introduces additional challenges. Wind turbine blades consist mainly of composite materials, which are difficult to recycle using conventional methods. Similarly, nacelle components contain complex assemblies of metals, electronics, and permanent magnets, requiring deliberate processing solutions and routes. From a circularity perspective, towers represent the most straightforward case due to their steel composition and established recycling pathways.

The distinction between offshore and onshore activities is therefore important. Extensive dismantling, separation, and processing are typically performed onshore, where conditions are typically more controlled and cost-effective. This includes cutting, shredding, and material recovery processes. The availability of suitable infrastructure, such as port quays and EoL processing facilities are key bottlenecks at this moment.

3.4.3 Emerging solutions

Research and development in WTG decommissioning focuses mainly on reducing offshore intervention time, improving material recovery, and enabling higher-value recycling or repurposing pathways.

Some emerging solutions include:

- **Alternative lifting strategies** - Concepts such as single-lift removal, bunny-ear configurations, or rotor-nacelle assembly lifting aim to reduce the number of offshore lifts. These approaches can lower offshore time but introduce challenges related to crane capacity, stability, and transport logistics. Examples: DOT single lift WTG [15].
- **Advanced composite recycling** - Development of recycling techniques for blade materials, including thermolysis, chemical recycling (solvolysis), and

mechanical processing. These aim to recover fibres and resins, although scalability and economic viability remain challenges often due to uncertainty in volumes slowing down investments. Examples: CIRCLE4WIN [16], EoLO-HUBs [17], DecomBlades [18].

- **Permanent magnet recovery** - Solutions targeting reuse, repurposing, or recycling of rare earth materials in generators. These approaches are driven by the high value and supply risks associated with critical materials. Examples: Re2Mag project.
- **High-value steel recycling** - Innovations in short-loop recycling of tower steel, aiming to retain material quality and reduce energy consumption compared to conventional scrap recycling. Examples: Groeien met Groene Staal [19].

3.5 Ecology

This section synthesizes key messages from a selection of articles and reports [20, 21, 22, 23] into an overview on ecological effects during offshore wind farm decommissioning. It focuses on the main impact pathways during the decommissioning campaign and the ecological changes that can persist after components are removed (or left in place), while being explicit about where evidence is still limited.

Offshore wind farm decommissioning is moving from a theoretical end-of-life phase to reality in the upcoming decade, yet the ecological evidence base remains comparatively limited. Across the full lifecycle, installation and operation have been far more frequently assessed and monitored than decommissioning, mainly because only a small number of commercial offshore wind turbines have been fully dismantled to date. As a result, decommissioning impacts are often discussed using analogies with installation and operational effects, supported by expert judgement and scenario reasoning rather than extensive empirical before-and-after data. This creates a challenge for both environmental impact assessments (EIAs) and broader cumulative assessment frameworks, particularly in the Dutch context where decommissioning is not yet consistently treated as a distinct lifecycle phase in KEC assessments [22].

In current practice, many ecological assessments assume that decommissioning disturbances are temporary, local, and comparable to (or lower than) installation, but the underlying measurements, especially for underwater noise, sediment disturbance, and ecological recovery, are still sparse [20]. This matters because decommissioning is not only a period of disturbance, but it also represents a system transition in which artificial structures and associated ecological functions created during 20-30 years of operation may be removed (fully or partly), changing habitat availability, local food webs, and patterns of human use (e.g. whether fisheries exclusion continues).

3.5.1 Partial versus full removal

Ecological outcomes are dependent on the chosen removal strategy. Complete removal versus partial removal is not a technical detail, but is the main determinant of whether the post-decommissioning habitat becomes largely soft-sediment again or retains hard-substrate features and associated communities.

1. **Complete removal with seabed restoration** - aims to approximate the pre-installation seabed morphology and substrate state, but implies loss of developed hard-substrate communities and may enable the return of bottom trawling.
2. **Partial removal options** - reduce seabed disturbance during works (for example, leaving scour protection in place) and preserve part of the established hard-substrate ecological functions, but can conflict with legal norms, future seabed uses, and concerns about non-native species stepping-stones.

In the Dutch context, the baseline legal starting point remains complete removal, but the ecological debate is increasingly framed around whether “full clearance” is always ecologically desired, especially where scour protection supports high local biodiversity and where removal itself creates extended disturbance and emissions. This means that decommissioning cannot be described as having one single ecological effect. Instead, its effects should be presented as trade-offs between plausible end states. The Dutch research project Nature-friendly Decommissioning recently developed visually appealing and quite comprehensive infographics describing the ecological implications of the different removal scenarios [24].

3.5.2 Drivers of ecological effects during and after decommissioning

Ecological effects are best understood by separating (1) short-term effects during deconstruction activities from (2) long-term effects after decommissioning, which depend strongly on whether removal is complete or partial (for example, whether scour protection remains). This distinction is useful because the effects during removal are different from the effects that remain afterwards.

Short term:

- **Underwater noise and vibration** - Decommissioning generates underwater noise and vibration through cutting, lifting, extraction, dredging, and cable recovery. Depending on the methods used, this includes both continuous and intermittent sound from vessels and offshore tools. Although pile driving during construction is usually seen as the dominant acoustic pressure in offshore wind, decommissioning can still produce substantial noise, especially during foundation removal, and these activities may continue over extended periods due to weather and campaign logistics.
From an ecological perspective, noise and vibration may cause temporary displacement or behavioral disturbance in fish and marine mammals, with effects depending on proximity, duration, season, and background activity. In the Dutch North Sea, harbour porpoises and seals are likely to be the main higher-trophic species affected, as decommissioning noise can cause temporary disturbance or displacement [21]. The main issue is that measured noise data for decommissioning methods remain limited [20]. As a result, these impacts are recognised as potentially important, but the available evidence is still too limited to judge the severity with confidence.
- **Seabed disturbance and turbidity** - Removal of foundations, scour protection, and buried cables disturbs sediments and can increase turbidity. The ecological implications are strongly site-dependent. In more dynamic seabed environments,

communities may be relatively adapted to burial and sediment mobility, whereas in lower-dynamic areas disturbance can be more damaging and recovery slower [20]. Turbidity can also affect visual predators and, if coinciding with sensitive periods, potentially influence primary production locally through reduced light penetration. Importantly, although individual decommissioning events are often expected to be local and temporary, simultaneous or sequential decommissioning across multiple wind farms can create cumulative turbidity and seabed-disturbance pressures at broader scales.

- **Chemical pollution risks** - Decommissioning increases vessel activity and handling of components that may contain oils, resins, and other substances. The dominant framing in the decommissioning literature is risk-based, as spills are not expected to be routine. Still, the consequences can be significant, so prevention (for example, draining/containing fluids before removal) is treated as standard good practice. Chemical risks are often discussed alongside sediment disturbance because removal can also mobilize contaminants that settled during the operational phase [21].
- **Non-native species transfer during removal and transport** - Foundations and scour protection can host non-native species alongside native species. During decommissioning, a specific risk pathway is the transport of colonized structures to shore, potentially moving organisms between locations unless managed through handling protocols. Complete removal can reduce the stepping-stone function of an offshore wind farm for non-native species in the long run, but this benefit has to be weighed against the short-term transfer risk during removal operations.
- **Above-water disturbance (birds and bats)** - For seabirds, migratory birds, and bats, decommissioning replaces the continuous effects of an operating wind farm with a temporary period of vessel traffic, lighting, crane activity, and other disturbance. These effects are generally local and limited to the period of the works, but they can still be ecologically relevant when activities overlap with sensitive periods such as migration, breeding, moulting, or key foraging seasons.

Long term:

- **Loss (or retention) of artificial hard-substrate habitat** - Operational wind farms introduce extensive hard substrate, such as foundations and scour protection, into largely soft-sediment systems. Over time, foundations and scour protection can be colonized by marine growth and provide habitat functions such as shelter, feeding opportunities, and spawning surfaces that were not present in the original sandy seabed [20]. Complete removal therefore causes a direct loss of this artificial habitat and the communities that have developed on it. By contrast, partial decommissioning, especially where scour protection remains, can retain part of these habitat functions and associated communities. These structures can have ecological value, but that value is not the same everywhere. It depends on factors such as the structure itself, the type of substrate, local hydrodynamic conditions, and the surrounding ecological setting. Reviews point to examples of artificial-reef effects at offshore structures, but they also show that the evidence is still too limited to conclude that leaving structures in place generally leads to long-term ecological benefit in all cases [21]. For that

reason, decommissioning decisions are best based on site-specific ecological conditions and a clear objective, such as restoring the original seabed or retaining some of the habitat that developed during operation.

- **Fisheries exclusion, return of bottom disturbance, and secondary ecological change** - During operation, many offshore wind farms are closed to bottom trawling, which reduces seabed disturbance in areas that are otherwise heavily used. This can benefit longer lived benthic species and, in some places, support the development of biogenic reefs [20]. After decommissioning, those benefits may decline if bottom trawling returns. This does not depend only on whether the wind farm is removed, but also on what is left behind. If structures such as scour protection remain, they may still limit some bottom-disturbing activity, whereas full removal may allow trawling to return more widely. The ecological outcome therefore depends partly on how fisheries are managed after decommissioning, as well as on the chosen removal strategy.
- **Hydrodynamics and stratification-related effects** - Large groups of structures can affect local mixing and stratification in the water column [20]. This is usually discussed for the operational phase, but it also matters for decommissioning because full removal also removes the structures that may cause these effects. Some decommissioning studies describe monopile removal as a possible ecological benefit in this respect, because full removal also removes the structures that may affect local mixing and stratification. The ecological importance of this effect likely depends on scale and local conditions, but the available evidence is still limited.
- **Bird and bat impacts after turbine removal** - After decommissioning, the picture changes because some operational effects disappear once turbines are gone. Under full removal, collision risk and turbine-related barrier effects are expected to largely disappear, making the area more similar to its pre-construction state for birds and bats. At the same time, some species can use offshore structures for resting, and those opportunities are also lost if all above-water structures are removed. The long-term outcome is hard to predict and heavily depends on species, location, and the removal strategy chosen.

3.5.3 Cumulative effects

Decommissioning will increasingly occur at scale, as multiple projects may reach end-of-life within overlapping time windows, and each project can require multi-season campaigns. This creates potential for cumulative disturbance (noise, turbidity, vessel traffic) that is not captured by single-project framing. The state-of-the-art response is to advocate explicit cumulative assessment and to avoid relying solely on assumptions that effects are “temporary and local,” especially when those local effects repeat across many sites.

3.5.4 Baseline and long-term ecological objective

Ecological assessments also face a baseline challenge: “returning to pre-installation conditions” is not always straightforward, because the North Sea ecosystem changes over decades due to climate variability, fisheries, eutrophication dynamics, and other offshore developments. Decommissioning decisions therefore require clarity about what “baseline” means in practice: is the reference point the historical pre-wind seabed, the current state at end-of-life (including established reef communities), or a policy-defined

ecological target? Several Dutch-focused discussions emphasize that the absence of long-term ecological baselines and a shared long-term ecological vision makes consistent evaluation of decommissioning impacts difficult, and that monitoring before, during, and after decommissioning is essential to improve future assessments [22].

3.5.5 Assessment and monitoring in practice

Ecological assessment of decommissioning is still developing. In practice, decommissioning is often only briefly covered in project EIAs, and in the Dutch context it is not yet consistently treated as a distinct lifecycle phase in KEC assessments [22]. Because empirical evidence remains limited, decommissioning effects are still often assessed through analogy with construction and operation, supported by expert judgement and scenario-based reasoning rather than strong before-and-after field datasets.

This has two practical consequences. First, assessments need to be explicit about uncertainty, including which effects are well supported, which are inferred from comparable activities, and which depend mainly on assumptions about removal methods or end states. Second, monitoring becomes especially important. Recent Dutch work argues for targeted monitoring before, during, and after decommissioning, so that future assessments rely less on analogy and more on decommissioning-specific evidence [22].

More broadly, review work on offshore wind biodiversity assessment also points to the need for stronger cumulative assessment, more consistent indicators, and better regional data sharing. Project-by-project monitoring alone may not be enough to understand population-scale or ecosystem-scale effects if many wind farms are decommissioned within overlapping time windows [21].

3.6 Legislation and regulations

The decommissioning of offshore wind farms in European waters is governed by a combination of international conventions and regional agreements. The most relevant ones are the United Nations Convention on the Law of the Sea (UNCLOS), the International Maritime Organization (IMO), and the OSPAR Convention [25] [26]. It is important to note that these frameworks were originally developed primarily for the O&G sector. As a result, their direct application to offshore wind remains subject to interpretation, and further clarification is currently being developed.

UNCLOS

UNCLOS establishes the general obligation to remove offshore installations at end-of-life:

“Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation (...) Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States.”

While full removal is the default expectation, UNCLOS allows for partial removal, provided that safety, environmental protection, and other sea users are appropriately considered.

IMO guidelines (Resolution A.672)

The IMO provides more detailed guidance through Resolution A.672, which requires that:

“abandoned or disused offshore installations or structures (...) are required to be removed, except where non-removal or partial removal is consistent with [established] guidelines and standards.”

Partial removal may be permitted when justified on the basis of:

- Safety for navigation and offshore operations;
- Technical feasibility;
- Environmental considerations.

OSPAR Convention

The OSPAR Convention provides the most detailed regional framework for offshore decommissioning in the North Sea. Its latest guidance (OSPAR Agreement 2024-04) introduces a clear preference for full removal (“complete removal” as baseline). Next to that a structured comparative assessment process to evaluate decommissioning options is proposed alongside requirements to demonstrate that risks are reduced to ALARP (As Low As Reasonably Practicable) and a requirement to demonstrate “best endeavours” before any derogation (e.g. partial removal or leave-in-place) can be granted. The guidance clarifies expectations for national authorities, consultation procedures among Contracting Parties, assessment of safety, technical feasibility and environmental impacts, and requirements for transparency, documentation, monitoring, and post-project knowledge sharing to ultimately reduce the number of derogations granted.

Importantly, OSPAR rules are currently being further developed to better address offshore wind-specific applications, including potential adaptations for structures such as monopiles, cables, and scour protection.

NL specific legislation and regulations

For EU wide there is no specific legislation for the decommissioning of offshore wind farms [25]. At the national level, some countries prescribe additional regulations and registrations for the decommissioning of wind farms;

The Netherlands has the Offshore Wind Energy Act, which stipulates that the wind farm must be completely removed at the end of its lifespan. However, it is possible to obtain permits for partial removal. The guideline here is that the owner is responsible for leaving the site in the same condition as before the wind farm was built. There is some uncertainty regarding the removal of scour protection.

4 Workshop results and prioritization table

4.1 Expert and stakeholder workshop

The expert and stakeholder workshop brought together 32 participants from industry, research, government and non-governmental organisations to discuss eco-friendly decommissioning of offshore wind farms in the Dutch North Sea. The workshop was held on 7 April 2026 in Amsterdam and was organised around three thematic rounds:

1. operations and logistics;
2. legislation, monitoring and ecology;
3. and recycling and end-of-life.

Across these sessions, participants identified challenges, proposed solution directions, and reflected on practical experiences and knowledge gaps for the main offshore wind farm subsystems.

The workshop outputs were subsequently translated into structured challenge and solution statements, classified by subsystem, theme and uncertainty level. These outputs should be read as stakeholder input rather than as validated facts or consensus conclusions. For that reason, this section does not attempt to reproduce all individual statements. Instead, it synthesises the main patterns that emerged from the discussions, with emphasis on the issues and solution directions that recurred most clearly across participants and sessions. The complete structured workshop output as translated from the post-its collected is included in Appendix A.

Although offshore substations were also discussed during the workshop, the synthesis below focuses on foundations, scour protection, cables and wind turbines, in line with the main analytical scope of this study.

4.1.1 Foundations

For foundations, the discussions were dominated by uncertainty around the feasibility, maturity, and consequences of full removal. Participants repeatedly referred to uncertain soil conditions around monopiles after long periods in the seabed, the limited track record of vibro-extraction methods, and the general sense that removal technology is not mature yet. These technical concerns were closely connected to practical constraints such as vessel availability, interaction with scour and cable removal, large onshore material volumes, and short decommissioning timelines prescribed by permits. Environmental impacts, particularly noise, sediment disturbance, bio-fouling hazards due to marine growth, and benthic effects, were also raised as recurring concerns.

The proposed solution directions for foundations were aimed less at identifying one preferred removal method and more at reducing uncertainty. Participants frequently pointed to the need for demonstration projects and broader data sharing to build confidence in removal approaches. Monitoring of soil conditions and seabed state before and after decommissioning was also put forward. In parallel, several contributions emphasised case-by-case assessment and comparative methods such as LCA when

weighing full and partial removal, particularly where steel recycling is technically feasible but the wider trade-offs (e.g., costs) remain uncertain.

4.1.2 Scour protection

The scour protection discussions moved quickly beyond removal efficiency alone to the broader question of whether full removal is always the most appropriate end state. Participants repeatedly noted that scour protection can develop ecological value over time and that complete removal may destroy habitat that has formed during the operational phase. At the same time, removal was described as technically difficult, especially where scour has become sediment-filled, redistributed or partly buried. Participants also questioned how complete removal could realistically be verified, and several pointed to the absence of a clear standard for when a site can be considered sufficiently cleaned.

Several participants proposed selective or partial removal, for example by retaining high-value scour and removing only lower-value material. Others pointed to design-for-decommissioning approaches, in which scour protection is designed from the outset to support both ecological function and later end-of-life choices. Monitoring featured prominently in these discussions, with suggestions including ROV inspection, eDNA, biodiversity indicators and pre- and post-decommissioning benchmark programmes to support more evidence-based decision-making. Circular pathways were also discussed, particularly reuse of removed stones in other offshore applications, although participants also highlighted persistent barriers related to mixed grading, sediment contamination, storage and cleaning capacity.

4.1.3 Cables

For cables, participants repeatedly mentioned cable crossings, export cable landfalls, older wind farm layouts and uncertain burial conditions as practical obstacles to removal. In some cases, they questioned whether removal is proportionate at all, particularly where cables are deeply buried or difficult to access. Environmental concerns were also raised around seabed disturbance during removal, the effects of vertical pulling, and the longer-term behaviour of plastic cable components if cables are left in situ.

The solution directions proposed for cables combined practical removal improvements with more selective decision-making. Participants referred to pull-and-cut methods on the vessel, stepwise recovery concepts and selective removal strategies in which difficult sections, such as crossings, may be left in place where justified. Several statements also pointed to the need for ecological assessment to determine when removal may cause more disturbance than benefit. On the circularity side, the workshop made clear that current recycling routes remain focused mainly on metals, especially copper, while materials such as XLPE receive far less attention. Further development of polymer recycling and other reuse concepts was therefore identified as an important need.

A second recurring theme for cables was liability in partial removal cases. Participants repeatedly questioned who remains responsible when cables or cable sections are left behind, how future responsibilities should be handled, and how inconsistent requirements between stakeholders affect removal choices. This suggests that effective

cable removal will depend not only on improved techniques, but also on clearer rules around leave-in-place options, responsibilities and acceptable end states.

4.1.4 Wind turbines

For wind turbines, the discussions were shaped primarily by logistics and end-of-life chain readiness. Participants repeatedly referred to the lifting demands of larger turbines, limited availability of specialised vessels and handling equipment, port congestion, and limited onshore handling capacity. Blade removal in particular was seen as operationally challenging, while broader planning and sequencing issues were also mentioned frequently. Some participants pointed to reverse logistics/feeder concepts as potentially promising, but these were generally discussed as ideas that still require validation rather than proven solutions.

The circularity discussion for wind turbines focused on uncertainty around reuse and the limitations of the current end-of-life chain. Participants questioned whether turbines or components should be reused or recycled, noting that remaining useful life is often unknown and that documentation and quality data are frequently insufficient to support credible reuse decisions. Structural health monitoring and better data sharing were therefore repeatedly proposed as enabling measures. At the same time, the workshop made clear that recycling challenges remain substantial, especially for blades, large components and mixed material streams. Proposed solution directions included regional recycling hubs near ports, better handling of chemical waste, and further development of higher-value routes such as permanent magnet reuse and green steel recycling.

Compared with foundations, scour protection and cables, the discussion on wind turbines was less centred on regulatory uncertainty and more on the practical readiness of the supply chain. The main message was that turbine decommissioning is not only an offshore lifting challenge, but also a data and processing challenge, with reuse, recycling and logistics still only partly mature.

4.1.5 Cross-cutting observations

Across the workshop, one recurring point was that many decommissioning decisions are still being made with limited decommissioning-specific evidence. This came back in different ways across subsystems: uncertainty around foundation removal performance, questions about the ecological effects of scour and cable removal, and limited information to support reuse decisions for wind turbine components. As a result, participants repeatedly pointed to the need for demonstration projects, monitoring, and better data sharing to reduce uncertainty in future projects.

A second recurring theme was that decommissioning is not only a question of removal technique, but also of the intended end state of the site. For scour protection, cables and foundations in particular, discussions repeatedly returned to the question of whether full removal is always the most sensible outcome, or whether partial removal may in some cases lead to a better balance between ecological impact, technical feasibility and cost. Those discussions were closely linked to uncertainty around permitting, liability, monitoring responsibilities and acceptable residual conditions.

The workshop also made clear that key bottlenecks are not limited to offshore operations. Vessel availability, lifting capacity and offshore logistics remain important, but participants also repeatedly raised concerns about port space, onshore handling and processing capacity, recycling routes, and the availability of data needed to support reuse or end-of-life decisions. In that sense, several of the challenges identified in the workshop were supply-chain and system-integration issues rather than isolated subsystem problems.

Taken together, the workshop did not point to one preferred decommissioning route. Instead, it highlighted a need for stronger evidence, clearer boundary conditions for decision-making, and better alignment between offshore removal strategies and the onshore systems needed to process what comes back to shore. These workshop insights, together with the desk study, informed the innovation areas and prioritisation presented in the next section.

4.2 Innovation area mapping and prioritization

Based on the state-of-the-art review and the outcomes of the stakeholder workshop, a consolidated overview has been developed of innovative solutions and potential pathways to enable offshore wind farm decommissioning to become both economically viable and environmentally responsible. The analysis is focused on the Dutch offshore wind context and brings together decommissioning solutions, ecosystem-supporting approaches, and circular end-of-life (EoL) strategies across the main subsystems.

The defined innovation areas are intentionally formulated at a relatively high level. This reflects a deliberate choice to prioritise the identification of key needs and challenges, rather than to advocate for specific technical solutions. The selection and validation of concrete technologies should be considered an outcome of subsequent research, development, and demonstration activities. This approach allows for flexibility in exploring alternative solutions and avoids prematurely narrowing the innovation space.

The identified innovation areas have been assessed using the qualitative multi-criteria framework described in Section 2.4. Each area was evaluated across the six dimensions of cost reduction potential, ecological footprint reduction, circularity impact, technical readiness, regulatory readiness, and Dutch industry potential. The results of this assessment and the resulting prioritisation are summarised in Table 4.1. The table represents a structured snapshot of the detailed scoring analysis, which is maintained in an accompanying Excel dataset.

The weighting applied to the different criteria is arbitrary but aims to reflect their relative importance for innovation policy and decision-making. While inherently indicative and not based on quantitative assessment, this weighting was chosen to strike a balance between impact (e.g. cost, ecology, circularity), strategic relevance for the Dutch industrial ecosystem, and feasibility (technical and regulatory readiness).

The generally high scores assigned in the Dutch industry potential category reflect the strong position of the Dutch offshore sector, supported by a well-established supply chain

and the presence of leading original equipment manufacturers for key balance-of-plant components such as monopiles and cables.

Table 4.1 Prioritizing offshore wind farm decommissioning innovation areas & solution pathways.

Foundations							
Baseline: partial removal 6m below seabed + steel recycling							
Title	Cost reduction potential	Ecological footprint reduction potential	Circularity potential	Technical readiness	Regulatory readiness	Dutch industry potential	Priority
Methods/technologies for full pile extraction in different soil conditions	3	2	3	2	3	3	2.8
Methods/technologies for high-value steel recovery from removed MP foundations	2	2	3	3	3	3	2.6
Design principles & monitoring techniques for easier pile removal (e.g. slip joint)	3	2	2	1	3	3	2.5
Methods/technologies for handling & pre-processing of removed MP foundations (e.g. cutting, cleaning)	2	2	3	2	3	3	2.5
Methods/technologies for (cut) pile transport (e.g. wet-towing, sea fastening)	3	2	1	2	3	3	2.4
Methods/technologies for grouted TP removal	2	2	2	3	3	3	2.4
Eco-enhancing foundation designs for leaving parts in situ	2	3	1	2	2	3	2.3
Circular design principles and business models for MP foundations (e.g. return systems)	1	2	3	1	3	3	2.2
Methods/technologies for internal pile dredging	3	1	1	2	2	3	2.1
Methods/technologies for internal pile cutting	3	1	1	3	1	3	2.1
Methods/technologies for (cut) pile lifting (e.g. bouyancy-assisted operations)	2	2	1	2	3	3	2.1
Methods/technologies for processing & sorting of grouted connections	1	1	2	2	3	3	1.9
Methods/technologies for external pile cutting	2	1	1	3	1	3	1.9
Methods/technologies for removal of marine growth from piles	1	2	2	2	2	2	1.8
Methods/technologies for secondary steel removal	1	1	1	3	3	3	1.7
Methods/technologies for (cut) pile handling & down-ending	1	1	1	3	3	3	1.7
Methods/technologies for external dredging & excavation	1	1	1	3	2	3	1.7
Scour protection							
Baseline: full removal via grab dredgers, uncertain EoL strategy							
Title	Cost reduction potential	Ecological footprint reduction potential	Circularity potential	Technical readiness	Regulatory readiness	Dutch industry potential	Priority
Ecosystem-enhancing scour protection technologies for leaving in situ (e.g. artificial reefs)	3	3	3	2	2	2	2.7
Methods/technologies for reuse/repurposing of scour protection	2	2	3	2	3	3	2.5
Methods/technologies for removal of scour protection rocks (e.g. specialized tools, vessels)	3	1	2	2	3	3	2.4
Designs principles/methods/technologies for reduced scour protection	3	2	2	2	3	2	2.3
Designs principles & technologies for easier removal of scour protection	3	1	2	2	3	2	2.1
Methods/technologies for handling & pre-processing of removed scour protection (e.g. sorting, cleaning, crushing)	2	2	2	2	3	2	2.1
Circular design principles and business models for scour protection (e.g. return systems, offshore storage)	2	1	3	1	3	2	2.0
Methods/technologies for recycling of scour protection	1	1	2	2	3	3	1.9

Inter Array and Export Cables							
Baseline: full removal via pulling by PSV, recycling of metals							
Title	Cost reduction potential	Ecological footprint reduction potential	Circularity potential	Technical readiness	Regulatory readiness	Dutch industry potential	Priority
Circular design principles and business models for IACs (e.g. return systems)	2	2	3	1	3	3	2.5
Methods/technologies for on-deck handling, cutting, and storing (incl. specialized vessels, tools)	2	2	2	2	3	3	2.3
Methods/technologies for gentle IAC removal for higher value retention and reduced seabed disturbance	1	2	3	2	3	3	2.3
Methods/technologies for handling & pre-processing of removed IAC (e.g. sorting, separation)	2	2	2	1	3	3	2.3
Design principles & monitoring techniques for easier IAC removal	2	2	1	2	3	3	2.1
Methods/technologies for IAC pulling in complex soil conditions	2	1	1	2	3	3	1.9
Methods/technologies for unmanned subsea operations (e.g. WROVs for cutting, gripping, and recovery of cable)	1	2	1	2	3	3	1.9
Methods/technologies for handling cable crossings	1	1	1	2	3	3	1.7
Methods/technologies for removal and separation of cable protection systems	1	1	1	2	3	3	1.7
Methods/technologies for handling export cable onshore landing points	1	1	1	2	3	3	1.7
Wind turbines (WTG)							
Baseline - Reversed installation by JUV (shuttle strategy), steel recycling, blade incineration/cement co-processing							
Title	Cost reduction potential	Ecological footprint reduction potential	Circularity potential	Technical readiness	Regulatory readiness	Dutch industry potential	Priority
Methods/technologies for rotor assembly removal	3	2	1	3	3	3	2.4
Methods/technologies for transport of removed WTG assemblies	3	2	1	3	3	3	2.4
Methods/technologies for generator & permanent magnets reuse or recycling	1	2	3	2	3	3	2.3
Methods/technologies for composite material (e.g. blades, nacelle) recycling enabling higher value retention	1	2	3	2	3	3	2.3
Methods/technologies for nacelle removal	2	2	1	3	3	3	2.2
Methods/technologies for tower (sections) removal	2	2	1	3	3	3	2.2
Design principles & monitoring techniques for WTG component lifetime extension/reuse	2	2	3	2	3	1	2.0
Design principles & monitoring techniques for easier WTG dismantling	3	2	2	1	3	1	2.0
Methods/technologies for on-deck pre-processing of WTG assemblies/components	1	1	2	2	2	3	1.8
Offshore substation (OSS)							
Baseline - Reversed installation by floating heavy lift vessel (shuttle strategy)							
Title	Cost reduction potential	Ecological footprint reduction potential	Circularity potential	Technical readiness	Regulatory readiness	Dutch industry potential	Priority
Design principles for easier OSS removal (e.g. modular design)	2	2	2	2	3	3	2.3
Design principles & monitoring techniques for OSS component lifetime extension/reuse	1	2	3	2	3	3	2.3
Methods/technologies for OSS component sorting and pre-processing	1	2	3	2	3	3	2.3
Methods/technologies for OSS lifting	2	2	1	3	3	3	2.2
Methods/technologies for OSS transport	2	2	1	3	3	3	2.2

5 Conclusions

Decommissioning is a great opportunity for the Dutch offshore wind industry. The Netherlands has all the knowledge, experience, infrastructure, and technology to be a world leader in the offshore wind EoL market. To make this happen it is key that the first Dutch decommissioning projects are leveraged as opportunities for technology development, innovation, and sector-wide learning.

5.1 Challenges and solutions in decommissioning

Based on the study and input from stakeholders, the following challenges have been identified for the decommissioning of offshore wind farms:

- **Regulatory uncertainty.** Permit provisions are often conflicting with OSPAR guidelines, which were anyhow developed for O&G and are currently being updated.
- **Technology development bottlenecks.** Technologies for (full) removal are still under development, and their progression in technology readiness suffers from the limited opportunity of testing solutions in relevant and operational environments (TRL 6/7). This is typically due to a combination of the high costs and risks of running such tests, and the difficult reproducibility of relevant conditions in controlled environments due to scale or long-term nature of relevant conditions (e.g. soil settlement, ecosystem formation, etc.).
- **Mismatching techno-economic expectations.** The lack of uniform offshore wind specific EoL rules and the limited attention devoted to end-of-life in the early offshore wind development projects that will be the first to be decommissioned creates serious mismatches in expectations toward the techno-economic feasibility of alternative removal strategies. For example, full removal may be demanded for early sites despite the lack of proven technologies commercially available to do so. Another relevant example for the Netherlands, is the 120 k€/MW decommissioning bank guarantee used since 2016, which was intended for full removal of subsystems but in fact can hardly cover the removal of 3-5 MW wind turbines alone.
- **Market maturity & operational risks for early projects.** The lack of field experience and the fact that (full) removal technologies have not yet been proven at scale significantly raise the operational risks (financial, environmental, etc.) of executing the first wave of decommissioning projects of the first-generation offshore wind farms.
- **Infrastructure availability.** Space on port quays for handling and processing large volumes of components is limited, especially where competing with installation projects. Investments in new infrastructure development or expansion of existing infrastructure are limited and delayed by the uncertainty in the timeliness of EoL volumes, the lack of coordination across different countries in the North Sea Region (few centralized EoL hubs vs distributed processing capacities), and the limited maturity of offshore wind Re-X (Reuse, Repower, Refurbish, Recycle) value chains.

- **Uncertainty on ecological & environmental footprint of removal strategies.** The environmental impact of alternative removal strategies is not (quantitatively) defined and there is no harmonized LCA method for wind power to assess it consistently so that outcomes are directly comparable.
- **Re-X value chain maturity.** Offshore wind farm EoL component processing capabilities and Re-X value chains are still underdeveloped due to uncertainty about EoL policy, lack of volumes, high investment costs, and limited demand for the end products.

To identify feasible options and solution pathways for (eco-friendly) decommissioning, it is important to distinguish between older, first-generation offshore wind farms and more modern offshore wind farms.

First generation, old offshore wind farms need:

- Realistic expectations regarding removal requirements, based on applicable regulation and techno-economic feasibility.
- A pragmatic, flexible, and collaborative approach from government bodies when assessing compliance with removal requirements.
- Clarity on (long-term) liability and monitoring requirements where components or sections are left in situ (e.g. cables, scour protection, and foundations).
- Short-term solutions. These could be supported through high-TRL innovation grants to accelerate near-term technology development, reduce the risks of early removal projects, and, at the same time, promote and ensure the sharing of data and lessons learned.

Modern & future farms need:

- Alignment of removal requirements with the commercial development of suitable technologies. Full removal may remain the standard provided that suitable technology is further developed.
- Incentives on environmental footprint reduction and circular EoL strategies in new development tenders, guided by long-term strategies that balance ambitions with feasibility and cost considerations (the Routekaart Wind op Zee is a great example [27]). Environmental responsibility is a key source of competitive advantage for Dutch companies acting in the offshore wind industry.

5.2 Prioritizing innovative solutions in (eco-friendly) decommissioning

The prioritization analysis highlighted a set of key innovation areas across the main offshore wind subsystems. These areas reflect the highest potential to deliver combined benefits in terms of cost reduction, environmental performance, circularity, and strategic relevance for the Dutch offshore wind ecosystem. Innovation pathways related to offshore substation removal have been excluded from this analysis, given their relatively limited impact when expressed on a per-MW basis in the Dutch context (typically involving a single foundation per site).

The following key innovation areas, ordered by subsystem, emerged from the proposed mapping and ranking. Innovations areas associated with offshore substation removal have been excluded due to the moderate impact of those operations when normalized on a per-MW basis (as normally there is only one foundation per site in the Netherlands).

- **Monopile foundations.** For both existing and modern wind farms, high-potential innovation areas focus on the further development and demonstration of full pile removal technologies to enable compliance with prevailing regulatory requirements (e.g. under OSPAR). In parallel, there is significant potential in improving pre-processing and recycling processes to maximise recovery of high-value steel fractions. For future wind farms, additional opportunities lie in design-for-decommissioning approaches (design-for-EoL), enabling more efficient removal of piles, reduced environmental impact, and improved circularity performance.
- **Scour protection.** Scour protection emerges as a critical cost and impact driver. The development of specialized offshore technologies for efficient removal of scour protection rocks is a key priority, particularly for existing wind farms where the complexity of full removal requirements may have been underestimated. In parallel, there is strong potential in developing reuse and repurposing pathways for recovered materials. For future wind farms, designing scour protection systems that enhance biodiversity and retain ecological value over time offers a promising pathway. Such approaches could vouch for in-situ retention, thereby avoiding the environmental and operational impacts associated with scour protection removal.
- **Cables.** Key innovation opportunities relate to improving the efficiency and scalability of cable removal and processing. This includes the development of pre-processing technologies, which address the currently labour-intensive nature of handling, cutting, and transporting stretches of inter-array and export cables. In addition, the development of “gentle” extraction techniques may contribute to reducing seabed disturbance, while circular business models and improved recycling pathways can increase material value retention. Relevant experience from adjacent sectors, such as telecommunications, could be leveraged to accelerate progress.
- **Wind turbines.** For wind turbines the highest potential lies in improving the efficiency of removal and transport operations, which are major cost drivers in decommissioning campaigns. Innovations targeting lifting strategies, logistics optimisation, and alternative dismantling concepts are therefore highly relevant. In addition, significant value can be unlocked through the development of circular end-of-life solutions for blades and generator components (e.g. permanent magnets), which remain the main bottlenecks for achieving fully circular offshore wind systems.

Encouragingly, research and innovation efforts are already underway in most high-potential areas and should be sustained and reinforced, with a strong focus on large-scale technology demonstration in offshore conditions.

6 Recommendations

Based on the outcomes of the study, our key recommendations to RVO and TKI for fostering eco-friendly decommissioning of wind farms in the Netherlands are:

- 1) **Design and develop an innovation programme** around the removal, transport, and processing of selected subsystems from the first sites to be decommissioned in the Netherlands (e.g. selected piles, cables, scour protection). The programme may contain multiple innovation projects aimed at demonstrating removal, transport, and processing technologies at scale, and it shall be coordinated by an independent party (e.g. TNO) in collaboration with relevant industry associations (e.g. GROW). To make the programme a success, a suitable framework would need to be defined to:
 - a. Incentivize owners, contractors, and knowledge institutes to participate in the innovation projects within the programme.
 - b. Adequately spread project costs and risks among relevant stakeholders (site owners, contractors, solution providers, government, etc.). All involved parties should have skin in the game to make it an industry-wide success.
 - c. Share benefits, including dissemination of datasets and lessons learned. This is only possible if condition b) is met. If all the risk is in fact born by one party, benefits will not be shared.
 - d. Separate concerns between the commercial part of the decommissioning project and the innovation scope around the removal of selected subsystems. Innovation projects need flexibility and have a risk profile which is hardly compatible with commercial removal & transport contracts.

A similar initiative is being undertaken in Germany with the Alpha Ventus wind farm [28], so the Dutch initiatives could built upon their lessons learned.

- 2) **Stimulate ecology, environmental footprint reduction, lifetime extension, and circular EoL measures in new offshore wind tenders.** Ecology incentives proved to be powerful stimuli for innovation and have become important sources of competitive advantage for the Dutch offshore industry. Initiatives such as the new circularity Routekaart may be effective, provided that:
 - a. Incentives on non-cost criteria should not jeopardize the importance of a low LCoE.
 - b. Evaluation criteria should be made as quantitative and measurable as possible, possibly based on one standard LCA approach to ensure consistent comparison of alternatives.
 - c. The gathering of critical component health data to support lifetime-extension and/or removal decisions is incentivized (e.g. monopile load measurements enable more accurate assessment of residual lifetime and extractability)
- 3) **Target subsidy instruments at:**
 - a. Stimulating the development of innovative removal strategies/technologies across different TRL levels. Although there are many promising technologies already at TRL >4, the potential impact of disruptive innovation should not be

underestimated given the low maturity of the industry. Therefore, low TRL research should not be forgotten.

- b. Understanding and quantifying life-cycle environmental impacts of alternative removal strategies (with consistent methodologies). From an ecology point of view, there is a need to clarify what is and is not desirable from a Dutch North Sea ecosystem perspective and define quantitative metrics to assess impacts.
- c. Developing sustainable Re-X routes for offshore wind farm EoL components and stimulating demand for resulting end products.
- d. Promoting port and Re-X infrastructure development, possibly in coordination with the other North Sea countries.
- e. Stimulating knowledge sharing and alignment of offshore wind EoL R&D at EU level. Multiple national initiatives are running in parallel at the moment and alignment and coordination would be beneficial for the pace of innovation.

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Appendix A. Workshop Post-its

This appendix presents snapshots of the Excel sheets summarising the aggregated Post-it inputs generated during the workshop sessions. The inputs have been consolidated, analysed, and categorised to facilitate interpretation. The results are organised according to the following main system components:

- Foundations
- Inter-array cables (IAC)
- Scour protection
- Wind turbine generator (WTG)



Foundations

ID	Subsystem	Theme	Type	Session(s)	Interpreted statement	Explanation / context	Original post-it wording
S1-FD-TECH-01	Foundations	Technical feasibility & removal methods	Challenge	Session 1	Soil behaviour around foundations is uncertain and difficult to predict prior to removal.	Ageing and consolidation affect extraction forces.	"Uncertainty soil behavior"; "Unknown soil: mitigation + vibro drive/extract"
S1-FD-TECH-02	Foundations	Technical feasibility & removal methods	Challenge	Session 1	Vibro-extraction methods have limited track record for decommissioning.	Uncertainty whether vibrohammer techniques are reliable after decades in seabed.	"Uncertainty of soil behavior (vibrohammer) track record testing"
S1-FD-TECH-03	Foundations	Technical feasibility & removal methods	Challenge	Session 1	Extraction of large monopiles embedded for 10+ years is technically challenging due to soil settlement.	Skin friction, suction, and fatigue effects may increase difficulty.	"Challenge: extraction of monopile that has been in the mud for 10+ years"
S1-FD-TECH-04	Foundations	Technical feasibility & removal methods	Challenge	Session 1	Increasing pile size is outpacing the development of removal technology.	Removal tools and methods lag installation scale-up.	"Increasing pile size – lag in removal technology"
S1-FD-TECH-05	Foundations	Technical feasibility & removal methods	Solution	Session 1	Develop evidence-based modelling and demonstrations for monopile removal.	Build confidence for regulators and industry decisions.	"SOL: develop evidence based modelling & demonstration for monopile removal"
S1-FD-TECH-06	Foundations	Technical feasibility & removal methods	Solution	Session 1	Apply automation and robotisation to foundation removal processes.	May reduce cost/risk; details not specified.	"SOL: automative, robotization"
S1-FD-ECO-01	Foundations	Environmental impact & ecology	Challenge	Session 1	Foundation removal causes noise, sedimentation, and benthic disturbance.	These impacts may hinder operations and permitting.	"Impact noise, sedimentation, benthos? May hinder decom operations"
S2-FD-ECO-02	Foundations	Environmental impact & ecology	Challenge	Session 2	Ecological impacts of foundation decommissioning are not well understood.	Need baseline and comparable monitoring data.	"Challenge: impact of foundation decommissioning (environment)"
S2-FD-ECO-03	Foundations	Environmental impact & ecology	Challenge	Session 2	Changes in soil behaviour over lifetime affect ecological outcomes post-removal.	Seabed may not return to original state; implications unclear.	"Change of soil behavior over lifetime wtr decom"
S2-FD-ECO-04	Foundations	Environmental impact & ecology	Solution	Session 2	Monitor soil conditions and seabed state after decommissioning.	Supports learning and validation of recovery assumptions.	"Solution: monitoring of soil conditions, done by owner and government"; "Post decom soil conditions/water depths"
S1-FD-OPS-01	Foundations	Operations & logistics	Challenge	Session 1	Availability of suitable vessels and equipment for foundation removal is limited.	Heavy-lift and extraction vessels are scarce/expensive.	"Specialized vessel availability"; "Type of vessel to be used"
S1-FD-OPS-02	Foundations	Operations & logistics	Challenge	Session 1	Interaction between foundation, scour, and cable removal complicates logistics.	Activities are interdependent and cannot be planned in isolation.	"Challenge: interaction of removal operations MP. Scour protection cable"
S1-FD-OPS-03	Foundations	Operations & logistics	Challenge	Session 1	Large volumes of foundation materials require onshore handling capacity.	Ports/yards may become bottlenecks.	"Large volumes of materials – where do they go? (onshore)"
S1-FD-OPS-04	Foundations	Operations & logistics	Challenge	Session 3/1	Decommissioning timelines prescribed by permits are short compared to operational complexity.	Time windows constrain planning flexibility.	"Germany 1 year... NL 2 years"
S3-FD-REC-01	Foundations	Recycling, re-use & circularity	Challenge	Session 3	Foundations were not designed/installed with decommissioning in mind (e.g., grout connections with TP).	Design choices create dismantling difficulty and cost.	"Foundations were not designed/installed with decom in mind"; "Challenge: efficient removal of grout connection"
S3-FD-REC-02	Foundations	Recycling, re-use & circularity	Challenge	Session 3	Removal of secondary steel (e.g., extended monopiles) is difficult.	Adds additional steps and uncertainty.	"Challenge: remove secondary steel (extended MP)"
S3-FD-REC-03	Foundations	Recycling, re-use & circularity	Solution	Session 2/3	Steel recycling is feasible; use LCA/assessment to decide leave vs remove & reuse.	Decision should compare impacts of full removal vs partial.	"Solution: recycling steel is not a problem... Foundation: LCA... decide on leave it... or decommission and re-use"
S3-FD-REC-04	Foundations	Recycling, re-use & circularity	Mixed	Session 2/3	Full extraction may introduce fatigue or structural risk during removal (suction, incomplete cut).	Removal loads may exceed expectations, increasing failure risk.	"Full extraction. MP fatigue"; "FOV risk. Sudden increase of loads (suction, incomplete cut)"
S1-FD-LEG-01	Foundations	Legislation, policy & governance	Challenge	Session 1	In the Netherlands, full removal of piles is assumed or expected.	Creates technical and cost pressure even where benefit is unclear.	"In NL we should remove piles completely"
S2-FD-LEG-02	Foundations	Legislation, policy & governance	Challenge	Session 2	Regulatory requirements for full extraction of foundations + scour are unclear.	Different interpretations by stakeholders and regulators.	"Actual full extraction requirements foundations + scour (regulatory)"
S2-FD-LEG-03	Foundations	Legislation, policy & governance	Challenge	Session 2	Regulators lack clarity on what they can allow/permit.	Leads to conservative decisions and uncertainty.	"Regulators do not know what they can allow/permit"
S2-FD-LEG-04	Foundations	Legislation, policy & governance	Solution	Session 2	Adopt case-by-case assessment for foundation decommissioning.	Avoids one-size-fits-all and supports ecological/technical nuance.	"Legislation solution: look at case by case per windfarm..."
S2-FD-LEG-05	Foundations	Legislation, policy & governance	Challenge	Session 2	ETS may incentivise exporting piles outside Europe for decommissioning.	Unintended economic/environmental effects; needs validation.	"E.T.S. creating unwanted economic benefit for exporting piles for decom outside Europe"

Cables

ID	Subsystem	Theme	Type	Session(s)	Interpreted statement	Explanation / context	Original post-it wording
S1-CB-OPS-01	Cables	Operations & logistics	Solution	Session 1	Pulling cables and direct cutting on vessel as a	Operationally efficient removal approach; may	"Pulling of cables and direct cutting on vessel"
S1-CB-OPS-02	Cables	Operations & logistics	Solution	Session 1	Selective cable recovery, e.g., abandonment of certain cable crossings.	Focus removal where feasible/valuable and leave problematic crossings.	"Selective cable recovery → e.g. abandonment of certain cable crossings"
S1-CB-OPS-03	Cables	Operations & logistics	Challenge	Session 1	Cable crossings complicate removal and recovery operations.	Crossings with other infrastructure are technically and legally difficult.	"Cable crossing challenges"; "Remove cables... problem: cable crossing?"
S1-CB-OPS-04	Cables	Operations & logistics	Challenge	Session 1	Export cable shore landing deburial and removal encounters problems.	Nearshore areas are buried/protected/inaccessible and regulated.	"Export cable shore landing deburial"; "Export cable removal encounters problems"
S1-CB-OPS-05	Cables	Operations & logistics	Challenge	Session 1	Cable removal techniques need improvement, especially for older wind farms.	Legacy designs/access constraints reduce feasibility of standard methods.	"Cable removal techniques need to be improved"; "Cable no ?? ... Access on older windfarms"
S1-CB-OPS-06	Cables	Operations & logistics	Challenge	Session 1	If cable is buried very deep (e.g., 8 m), it may not be worthwhile to remove it.	Deep burial increases cost and environmental impact; decision may be case-specific.	"If cable is buried under a sand dune (let's say 8M deep) is it still worthwhile to remove it?"
S1-CB-OPS-07	Cables	Ecology & environmental impact	Challenge	Session 1	Marine life disturbance during decommissioning of cables.	Removal disturbs benthic habitats and species.	"Marine life disturbance during decommissioning of cables"
S1-CB-OPS-08	Cables	Ecology & environmental impact	Challenge	Session 1	Vertical pulling during cable removal may cause environmental damage.	Extraction method may increase turbidity or seabed disruption.	"Challenge: env. Damage of vertical pulling during cable removal"
S2-CB-ECO-02	Cables	Ecology & environmental impact	Challenge	Session 1	If cables are left behind, what happens to plastics (PE) after decades?	Long-term degradation of insulation could become pollution/microplastics risk.	"If you leave cables what happens with the plastics (PE) after 10, 20, 50 years?"
S2-CB-ECO-03	Cables	Ecology & environmental impact	Solution (conditional)	Session 2	Partial removal or abandonment of cables based on ecological assessment.	Case-by-case decisions to minimise disturbance; depends on monitoring and permits.	"Case by case assessment"; "Leave in place nature reserve"
S2-CB-ECO-04	Cables	Ecology & environmental impact	Solution	Session 2	Exposed cables could be repurposed as an interconnector (dual purpose).	Conceptual repurposing; feasibility and safety/ownership unclear.	"Exposed cables dual purpose as interconnector"
S2-CB-REC-02	Cables	Recycling & end-of-life	Solution	Session 2	Move research for XLPE recycling to improve cable	Targets insulation material recycling rather than only	"Move research for XLPE"
S2-CB-REC-03	Cables	Recycling & end-of-life	Solution	Session 2	Chop cables into small pieces and use as cable fixation for new turbines.	Novel reuse pathway; likely needs validation for durability and safety.	"Chop cables in small pieces and use as cable fixation for new wind turbines"
S2-CB-REC-04	Cables	Recycling & end-of-life	Challenge	Session 2	Cable recycling focuses mainly on copper; other materials get too little attention.	Steel, lead, aluminium, and polymers have lower-value/less-developed recycling routes.	"Cable recycling mainly focused on copper..."
S2-CB-REC-05	Cables	Recycling & end-of-life	Observation	Session 2	Multiple cable materials can be recycled: lead, steel, copper, aluminium; XLPE remains a research need.	Highlights multi-material nature and need for broader recycling systems.	"Parts of cable you can recycle: lead, steel, copper, aluminum. Move research for XLPE"
S3-CB-REC-06	Cables	Recycling & end-of-life	Challenge	Session 3	Lack of demand for recyclable cable materials.	Market pull is weak, limiting investment in recycling	"Cables: lack of demand for recyclable materials"
S1-CB-LEG-02	Cables	Legislation & governance	Challenge	Session 1	Legislation is unclear on leaving cables in situ,	Uncertainty creates inconsistent practice and	"Cables: is legislation clear on leaving in-situ"
S1-CB-LEG-03	Cables	Legislation & governance	Challenge	Session 1	Lack of standardization: cutting vs spooling; TenneT expects complete export cable removal.	Different stakeholders impose different requirements; affects methods and cost.	"Cutting cables vs. Spooling. Tennet: basis is removal of complete export cable"
S1-CB-LEG-01	Cables	Legislation & governance	Challenge	Session 1	Tendering lacks clear obligations/incentives on cable decommissioning and sustainability.	Low weight of cable/sustainability criteria reduces uptake.	"No legislation in tenders for decom of cable..."
S2-CB-LEG-04	Cables	Legislation & governance	Solution	Session 2	Define which construction materials are acceptable to leave behind after decommissioning.	Clear rules reduce uncertainty and enable consistent permitting.	"Make legislation on which construction materials are acceptable to leave behind..."
S2-CB-LEG-05	Cables	Legislation & governance	Challenge	Session 2	Responsibility for structures left behind and ex-site management is unclear.	Long-term liability, monitoring, and maintenance responsibilities are unresolved.	"Who is responsible for structures left behind? How should ex-sites be managed?"
S2-CB-LEG-06	Cables	Legislation & governance	Challenge	Session 2	OSPAR reconsideration of full removal obligation creates policy uncertainty.	International guidance evolving; national application unclear.	"OSPAR: (re)consideration of full removal obligation. No policy clarity yet"
S2-CB-LEG-07	Cables	Legislation & governance	Solution (emerging)	Session 2	Advocate for flexibility in international frameworks (e.g. OSPAR).	Align offshore wind decommissioning with risk-based, flexible approaches.	"Opportunity → OSPAR is now drafting measures → advocate for flexibility"
S2-CB-MON-01	Cables	Monitoring & knowledge gaps	Challenge	Session 2	Lack of research on impacts of cable removal (incl. repair/maintenance) and related footprint (LCA/CO2).	Decisions may not be evidence-based; need research into environmental and carbon impacts.	"Lack of research on impact of removal of cables... (LCA... CO2 footprint for recycling"

Scour protection

ID	Subsystem	Theme	Type	Session(s)	Interpreted statement	Explanation / context	Original post-it wording
S1-SC-ECO-01	Scour	Ecology & environmental impact	Challenge	Session 1 (Ops & Logistics), Session 2 (Legislation/Monitoring/Ecology)	Removal of scour protection may significantly disturb marine ecosystems that developed around it.	Scour protection often acts as artificial reef; removal destroys established habitats.	"Scour protection have developed into ecological reefs"; "Destroying marine habitat created around scour protection in case of decommissioning"; "Potential disruption to ecology with complete foundation scour protection removed"
S1-SC-ECO-02	Scour	Ecology & environmental impact	Challenge	Session 1, Session 2	It is unclear whether ecological disturbance caused by scour removal is justified compared to leaving it in place.	Participants question proportionality: disturbance vs ecological benefit retained.	"Do you want to leave scour from nature perspective?"; "Does it matter compared to scale of North Sea and compared to scale of time?"
S2-SC-ECO-03	Scour	Ecology & environmental impact	Challenge	Session 2	Complete scour removal may eliminate high-value hard-substrate communities without clear ecological	Hard substrate communities are scarce and may have disproportionate biodiversity value.	"Elimination of hard substrate communities → value of communities"; "How much hard substrate is
S2-SC-ECO-04	Scour	Ecology & environmental impact	Challenge	Session 2	Removing and relocating scour stones may spread non-indigenous species.	Transfer of colonised stones can unintentionally introduce species elsewhere.	"Challenge Ecology: when removing and transferring the stones, we can spread non-indigenous species"
S2-SC-ECO-05	Scour	Ecology & environmental impact	Solution (conditional)	Session 2	Retain high-ecological-value scour protection and remove only lower-value material.	Selective or partial removal based on biodiversity assessments; depends on monitoring and regulation.	"Retain 'high value' eco scour → partial removal"; "Leave scour in place when biodiversity is high"
S2-SC-ECO-06	Scour	Ecology & environmental impact	Solution	Session 2	Design scour protection explicitly for ecological function and later decommissioning.	Anticipate end-of-life decisions at design stage (grading, materials, layout).	"Design scour for decommissioning"; "Nature-inclusive scour protection... what happens during
S1-SC-MON-01	Scour	Monitoring & knowledge gaps	Challenge	Session 1, Session 2	It is difficult to measure and prove ecological impacts of scour removal.	Lack of agreed indicators, baselines, and methods for impact assessment.	"How would the removal of scour protection impact the marine ecosystem & how do we measure it?"; "Determining impact (environmental/spatial)... When
S2-SC-MON-02	Scour	Monitoring & knowledge gaps	Challenge	Session 2	No clear standard for when a site is "sufficiently cleaned" after scour removal.	Especially problematic for redistributed stones or buried filter layers.	"How to determine when the seabed after decom is sufficiently cleaned."; "If 100% of rocks must be removed, how do you know it is 100%?"
S2-SC-MON-03	Scour	Monitoring & knowledge gaps	Challenge	Session 2	Monitoring requirements for decommissioning are unclear, costly, and responsibilities are not defined.	Uncertainty who monitors, how long, and who pays.	"Monitoring cost"; "Monitoring for decommissioning... Who is responsible?"
S2-SC-MON-04	Scour	Monitoring & knowledge gaps	Solution	Session 2	Use monitoring tools such as ROVs, eDNA, and biodiversity indicators to inform decommissioning	Data-driven decisions rather than blanket rules.	"Monitoring by ROV: ROV + e-DNA"; "Monitoring need: functional diversity..."; "Monitoring – scour
S2-SC-MON-05	Scour	Monitoring & knowledge gaps	Solution	Session 2	Establish pre- and post-decommissioning ecological benchmarks and research programmes.	Enables learning across projects and reduces uncertainty.	"Create a research programme..."; "Monitoring – benchmark for ecological monitoring"
S1-SC-OPS-01	Scour	Operations & logistics	Challenge	Session 1	Scour protection removal causes significant seabed disturbance and turbidity.	Physical removal disturbs sediments and benthic life.	"Scour removal – seabed disturbance"; "Challenge: environmental disturbance of SPL removal"
S1-SC-OPS-02	Scour	Operations & logistics	Challenge	Session 1	Removing double-graded, sediment-filled, or sand-wave-covered scour protection is technically difficult.	Scour changes character over time, complicating removal.	"Double gradings, sediment infilled, sand-wave-covered, scour protections are difficult to remove"
S1-SC-OPS-03	Scour	Operations & logistics	Challenge	Session 1	It is difficult to verify that all scour material has been removed.	Stones may be buried, scattered, or redistributed.	"Problem: how can you be sure that you have removed all the stones of the scour protection layers?"
S1-SC-OPS-04	Scour	Operations & logistics	Solution (conceptual)	Session 1	Design scour so that material migrates to a single collection area over the life of the asset.	Concept to simplify later removal or leave-in-place decisions; feasibility unclear.	"Scour solution – make scour bank collect all scour at 1 place"
S1-SC-REC-01	Scour	Disposal, re-use & recycling	Challenge	Session 1	Large volumes of removed scour require disposal or storage capacity that may not exist.	Both offshore handling and onshore space are limiting.	"Scour removal – onshore space required/disposal"; "Challenge: scale of landfill volumes of SPL"
S1-SC-REC-02	Scour	Disposal, re-use & recycling	Challenge	Session 1	Removed scour material is mixed with sediments and unsuitable for direct re-use; cleaning facilities at scale	Mixed grading + sediments require processing capacity not currently available.	"Removed scour protection materials are mixed gradings and sediments... facilities to 'clean' do not
S3-SC-REC-03	Scour	Disposal, re-use & recycling	Solution	Session 3, Session 2	Re-use scour stones in other offshore projects (e.g. cable crossings, new wind farms).	Avoids quarry extraction and transport of new rock; depends on specifications and regulation.	"Downgrade scour protection rocks to cable crossing protections"; "Design... reuse of scour"
S2-SC-REC-04	Scour	Disposal, re-use & recycling	Mixed	Session 2	Leaving scour in place may reduce new quarry extraction but prevents reuse elsewhere.	Trade-off between leaving for ecology vs circular reuse.	"Continued extraction from quarries when rock is left in place"
S2-SC-REC-05	Scour	Disposal, re-use & recycling	Observation	Session 2	The circular value of scour protection may be lower than expected.	Stones may only be reusable in lower-grade applications (or as crushed material).	"Challenge: 'low' circular value of SPL? Direct re-use or grinded re-use only?"
S2-SC-LEG-01	Scour	Legislation & governance	Challenge	Session 2	Current regulations favour full removal and leave little room for ecological nuance.	Blanket rules dominate permitting.	"Current regulations opt for blanket rule – full removal"; "Leave the scour intact. Problem: permit
S2-SC-LEG-02	Scour	Legislation & governance	Challenge	Session 2	No clear policy on partial removal of scour protection.	Creates uncertainty for developers and regulators.	"Legislation uncertainty: full removal vs. Partial"
S2-SC-LEG-03	Scour	Legislation & governance	Solution	Session 2	Move towards case-by-case, site-specific decommissioning decisions for scour.	Accounts for local ecology, future use, and seabed dynamics.	"Case by case assessment"; "Location specific approach..."
S2-SC-LEG-04	Scour	Legislation & governance	Solution (emerging)	Session 2	Advocate for flexibility in international frameworks (e.g. OSPAR) for offshore wind decommissioning.	Prevent oil & gas rules being applied uncritically to offshore wind.	"Opportunity → OSPAR is now drafting measures → advocate for flexibility"

Wind turbine (WTG)

ID	Subsystem	Theme	Type	Session(s)	Interpreted statement	Explanation / context	Original post-it wording
S1-WTG-OPS-01	WTG	Operations & logistics	Challenge	Session 1	Removal of larger next-generation WTGs requires very high lifting capacity.	22 MW class turbines push crane and vessel limits.	"WTG lifting capacity → 22MW"
S1-WTG-OPS-02	WTG	Operations & logistics	Challenge	Session 1	Availability of specialized vessels and handling	Decommissioning competes with installation and	"Specialized vessel availability"; "Handling equipment"
S1-WTG-OPS-03	WTG	Operations & logistics	Challenge	Session 1	Lack of port space and onshore receiving capacity for WTG components.	Ports may be congested with simultaneous build-out and decom.	"(limited) size of onshore receiving facilities"; "Space in port for WTG..."
S1-WTG-OPS-04	WTG	Operations & logistics	Challenge	Session 1	Planning and logistics are complex due to preparatory works and timelines.	Requires sequencing, permits, and long lead preparations.	"Preparatory works & timeline"; "Planning & logistics..."
S1-WTG-OPS-05	WTG	Operations & logistics	Challenge	Session 1	Efficiency of offshore blade removal is uncertain and	Blades are large, fragile, and difficult to detach	"Efficiency removal of blades (wow)"; "Blade
S1-WTG-OPS-07	WTG	Operations & logistics	Mixed	Session 1	Reversed logistics ("reverse feeder") concepts could improve efficiency but are unproven.	Concept borrowed from installation logistics; needs demonstration.	"Transport + MP reverse feeder?"; "Transport WTG's reverse feeder?"
S1-WTG-CIRC-01	WTG	Re-use, life extension & circularity	Challenge	Session 1	Uncertainty whether WTGs or components should be reused or recycled.	Depends on condition, certification, and market demand.	"WTG decom reuse or not?"; "Reuse WTG or reuse components"
S3-WTG-CIRC-02	WTG	Re-use, life extension & circularity	Challenge	Session 3	Remaining useful life (RUL) of older WTG components is unknown.	Different design margins across generations complicate reuse decisions.	"Challenge: with old WTG parts we don't know the RUL"; "engineering margins... much closer..."
S3-WTG-CIRC-03	WTG	Re-use, life extension & circularity	Challenge	Session 3	Lack of documentation and quality data prevents assessment for re-use.	Without condition data, re-use is hard to justify/insure/certify.	"Lack of sharing WTG quality to recyclers..."; "Proper documentation for re-use"
S3-WTG-CIRC-04	WTG	Re-use, life extension & circularity	Solution	Session 3	Use structural health monitoring and data sharing to support reuse decisions.	Data enables validation for second-life applications.	"Structural health monitoring data"; "Transparency, open access data sharing"
S3-WTG-CIRC-05	WTG	Re-use, life extension & circularity	Mixed	Session 3	Higher position on the R-ladder (reuse vs recycle) is not always optimal.	Reuse can increase risk/emissions if logistics or quality are poor.	"Is going higher on the R-ladder always better?"
S3-WTG-REC-01	WTG	Recycling & end-of-life	Challenge	Session 3	Blade recycling is not mature at scale.	Composite blades remain the main unresolved waste stream.	"Blades are the only remaining challenge to tackle at scale"; "Blade recycling not mature yet"
S3-WTG-REC-02	WTG	Recycling & end-of-life	Challenge	Session 3	Size and material purity of WTG components complicate recycling.	Large components exceed processing capacities; purity requirements high.	"Size of components"; "Material purity"
S3-WTG-REC-03	WTG	Recycling & end-of-life	Challenge	Session 3	Management of marine growth and chemical waste during dismantling is unclear.	Cleaning generates secondary waste streams needing treatment.	"Marine growth disposal, chemical waste?"; "Cleaning (marine growth)"
S3-WTG-REC-04	WTG	Recycling & end-of-life	Solution	Session 3	Develop recycling hubs near ports with sufficient	Centralised processing reduces logistics and enables	"Solution: recycling hubs near ports (Eemshaven)"
S3-WTG-REC-05	WTG	Recycling & end-of-life	Solution	Session 3	Explore green steel production and permanent magnet reuse as opportunities.	High-value streams may justify investment; details unclear.	"Opportunity for green steel production market"; "Recycle opportunity – permanent magnet re-use..."
S1-WTG-COST-01	WTG	Cost, market & supply chain	Challenge	Session 1	Decommissioning cost is not yet well integrated into electricity pricing.	Future decom liabilities remain economically abstracted.	"Pricing in the decommissioning cost into the price of electricity"
S3-WTG-COST-02	WTG	Cost, market & supply chain	Challenge	Session 3	End-of-life supply chain readiness is insufficient.	Recycling/transport/processing capacity lags expected volumes.	"EOL supply chain"; "Readiness & availability of supply chain"
S3-WTG-COST-03	WTG	Cost, market & supply chain	Challenge	Session 3	No level playing field yet for WTG decommissioning and reuse.	Inconsistent rules/incentives distort choices.	"No level playing field yet"
S2-WTG-LEG-01	WTG	Legislation & governance	Challenge	Session 2	Decommissioning legislation for WTGs is unclear or	Regulatory framework less explicit than in oil & gas.	"Legislation on decom does not really exist"
S2-WTG-LEG-02	WTG	Legislation & governance	Challenge	Session 2	OEM dependency complicates turbine dismantling and reuse.	IP, warranties, and proprietary designs may limit third-party dismantling.	"Turbine dismantling without OEM"
S2-WTG-LEG-03	WTG	Legislation & governance	Solution	Session 2	Use case-by-case, site-specific permitting for WTG decommissioning.	Avoids one-size-fits-all outcomes.	"Legislation & policy case by case, site specific"; "site specific assessment should be the base"
S1-WTG-MON-01	WTG	Monitoring, data & learning	Challenge	Session 1/2	Lack of shared data and demonstrations slows learning in WTG decommissioning.	Experience remains fragmented across projects.	"Data sharing + demo in controlled environment"; "connect research... network & dissemination"
S2-WTG-MON-02	WTG	Monitoring, data & learning	Solution	Session 2	Increase transparency and open access data sharing across the wind industry.	Could mirror oil & gas practice; reduces repeated uncertainty.	"Transparency sharing data experiences"; "One voice as wind industry 'like Oil & Gas'"

OSS

ID	Subsystem	Theme	Type	Session(s)	Interpreted statement	Explanation / context	Original post-it wording
S1-OSS-TECH-01	OSS	Technical design & feasibility	Challenge	Session 1	Difficulty to fully decommission OSS foundations, both technically and ecologically.	Large jackets/piles are hard to remove and removal can cause ecological disturbance.	"Difficulty to fully decommission substation foundation (technically) but also ecological disturbance"
S1-OSS-TECH-02	OSS	Technical design & feasibility	Challenge	Session 1	OSS size is not well aligned with future capacity needs or decommissioning realities.	Trend to larger-capacity substations may complicate removal and reuse/repowering concepts.	"OSS – size vs. Capacity in the market"
S1-OSS-TECH-03	OSS	Technical design & feasibility	Challenge	Session 1	Full removal of OSS jackets and piles may not be technically feasible.	Uncertainty whether jacket piles can be extracted completely in practice.	"Remove jacket of OSS completely. Can you remove piles?"
S3-OSS-TECH-04	OSS	Technical design & feasibility	Solution	Session 3	Design OSS with modular concepts to enable relocation or reuse.	Modularity could reduce decommissioning scope by allowing components to be reused or moved; feasibility depends on standards and interfaces.	"OSS: create modular design. Making one substation to new location"
S1-OSS-REUSE-01	OSS	Re-use, repurposing & lifetime extension	Solution	Session 1	Replace OSS topsides while reusing existing foundations for repowering / higher capacity.	Brownfield-style upgrade: avoid full foundation removal by replacing/upgrading topside equipment.	"Repowering OSS → replace topside with higher capacity"; "Re-use substation new wind lifetime?"
S1-OSS-REUSE-02	OSS	Re-use, repurposing & lifetime extension	Solution	Session 1	Reuse OSS as electricity hubs for other offshore applications (e.g., floating solar, charging, wave, airborne wind).	Repurposing the grid connection and platform infrastructure could enable continued use after wind farm end-of-life; depends on business case and permits.	"Use substation as electricity plug for floating solar, charging, wave "airborne wind""
S2-OSS-REUSE-03	OSS	Re-use, repurposing & lifetime extension	Solution	Session 2	Repurpose OSS for non-energy uses (e.g., military use; hydrogen/fusion production).	Ideas to extend asset function beyond wind operations; feasibility and desirability are uncertain and may be site-specific.	"Military use substations"; "Hydrogen/fusion production"
S3-OSS-REUSE-04	OSS	Re-use, repurposing & lifetime extension	Solution	Session 3	Replace OSS topside and reuse jacket foundation.	Limits offshore heavy-lift/removal scope to the topside while leaving/reusing the jacket (subject to regulation and integrity).	"Solution: OSS replace topside, reuse jacket foundation"
S1-OSS-OPS-01	OSS	Operations & logistics	Challenge	Session 1	OSS removal requires a unique, expensive heavy-lift vessel.	Very limited vessel availability/capability for removing large topsides/jackets drives cost and schedule risk.	"The need for 1 unique and expensive vessel for OSS removal"
S1-OSS-OPS-02	OSS	Operations & logistics	Challenge	Session 1	OSS decommissioning is expensive relative to other wind farm components.	Large mass and offshore heavy-lift logistics dominate costs (vessel day rates, port handling, transport).	"Expensive to decommission assets on offshore substation"
S1-OSS-OPS-03	OSS	Operations & logistics	Challenge	Session 1	Managing loss/transfer of generation capacity during OSS decommissioning requires careful planning.	Decommissioning may affect grid connection/availability; requires coordination with operators (and possibly phased work).	"Dealing with large ?? of generation during decommissioning. Proper planning"
S1-OSS-OPS-04	OSS	Operations & logistics	Observation	Session 1	OSS removal sequence and interdependencies matter (what is removed next / in what order).	Order of removing topside, jacket, piles, and connected assets affects logistics and feasibility; original note is vague.	"OSS piece next removal"
S2-OSS-ECO-01	OSS	Ecology & environmental impact	Challenge	Session 2	OSS foundations contribute to hard-substrate habitats that may be lost upon removal.	Substation jackets/foundations can act as artificial reef/hard substrate similar to scour; original wording was generic to hard substrate communities.	"Elimination of hard substrate communities → value of communities"
S2-OSS-ECO-02	OSS	Ecology & environmental impact	Challenge	Session 2	Ecological disturbance and benefits of OSS structures are not well quantified relative to removal cost.	Trade-off question: ecological value added by structures vs cost/impact of removal; needs metrics and baseline.	"What is the "value" of nature-added vs cost of removal?"
S2-OSS-LEG-01	OSS	Legislation, policy & governance	Challenge	Session 2	Unclear legislation and regulator uncertainty on allowing partial vs full removal of OSS structures.	Regulators may be unsure what they can permit; creates conservative decisions and uncertainty for reuse/partial removal.	"Regulators do not know what they can allow/permit"; "Legislation uncertainty: full removal vs. Partial"
S2-OSS-LEG-02	OSS	Legislation, policy & governance	Challenge	Session 2	Blanket full-removal obligations leave little room for OSS reuse or repurposing concepts.	One-size-fits-all rules can block innovations like leaving/reusing foundations or repurposing the substation.	"Current regulations opt for blanket rule – full removal"
S2-OSS-LEG-03	OSS	Legislation, policy & governance	Solution	Session 2	Apply case-by-case assessment for OSS decommissioning decisions.	Account for local ecology, technical feasibility, integrity, and future use rather than blanket rules.	"Legislation solution: look at case by case per windfarm..."
S2-OSS-LEG-04	OSS	Legislation, policy & governance	Solution (emerging)	Session 2	Advocate flexibility within OSPAR frameworks for OSS / offshore wind decommissioning.	International guidance is evolving; flexibility could enable risk-based partial removal and reuse where justified.	"Opportunity → OSPAR is now drafting measures → advocate for flexibility"



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