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Review

Decommissioning Offshore Wind Fixed Steel Pile Foundations: A Critical Review

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Abstract: Offshore wind has rapidly developed over the past three decades, with over 6000 fixed-bottom substructures installed in Europe alone as of 2022. Despite this progress, there has been limited focus on the end-of-life stages, particularly decommissioning, which is currently the default option. Sustainable offshore wind development hinges on effective decommissioning strategies for fixed-steel pile foundations. This review critically examines state-of-the-art pile-foundation-decommissioning methods recently tested in industry and academia, including partial-removal techniques like internal cutting and external cutting and full-removal approaches such as excavation and novel extraction methods. Key factors influencing decommissioning decisions, such as seabed disturbance, environmental impact, reuse potential, and cost, are discussed. Analyses reveal that current partial-removal strategies could render vast swaths of marine areas inaccessible for future development. In contrast, full removal through extraction may enable complete recycling and minimise post-decommissioning monitoring. However, significant knowledge gaps remain regarding novel extraction methods' scalability, technical feasibility, and economics. Extensive research encompassing engineering, environmental, and economic dimensions is essential to develop holistic pile-foundation-decommissioning solutions that facilitate the sustainable long-term growth of offshore wind.

Keywords: decommissioning; offshore wind; fixed foundations; pile foundations; mono-pile; partial removal; full removal; extraction

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1. Introduction

Offshore wind plays a pivotal role in the energy transition sector, which is projected to generate 10% of global electricity by 2050, requiring 1400 GW of installation capacity [1]. Europe considers it crucial to achieve carbon neutrality by 2050, necessitating 300–450 GW. The concept has evolved significantly since its inception at Europe's Vindeby farm, where onshore turbines were installed on concrete foundations in shallow water [2]. Today, offshore wind spans three major regions with over 60 GW of cumulative installed capacity: Asia-Pacific (34 GW), Europe (30.272 GW), and America (0.042 GW) [3]. Technological advancements have seen turbine capacities soar from 0.45 MW to 14 MW, a remarkable 3.011% increase [4]. Turbines have shifted from adapted onshore versions to purpose-built offshore designs. Despite its growth, offshore wind remains challenging due to its relative novelty and ongoing maturation across its lifecycle. However, its potential is immense, capable of generating over 420,000 TWh of electricity annually worldwide—more than 15 times the global electricity demand in 2021 [5,6]. The International Energy Agency estimates the global technical potential of offshore wind exceeds 120,000 GW. As technology advances and costs decrease, offshore wind is poised to impact global energy production significantly. It offers a sustainable solution to growing electricity demands while supporting decarbonisation efforts. The industry continues to evolve, addressing development, installation, and maintenance challenges. With increasing investment and technological innovation, offshore wind is set to play a crucial role in reshaping the world's energy landscape, contributing substantially to renewable energy goals and climate change mitigation strategies.

Offshore wind infrastructure draws extensively from oil and gas, featuring diverse substructures and foundations. These components vary in design, materials, and installation methods, creating numerous combination possibilities [7]. For example, tripod structures can utilise either conventional piles or suction buckets. Industry terminology often conflates "substructures", "support structures", and "foundations", causing confusion. Clarity in distinguishing these terms is crucial for effective communication and standardisation in the rapidly evolving offshore wind sector. As the industry grows, precise language becomes increasingly important for project planning, engineering, and regulatory compliance. This precision facilitates better understanding among stakeholders and supports the efficient development of offshore wind farms globally.

DNV categorises offshore wind turbine structures into two main components: the wind turbine and the support structure system [7]. The latter includes the transition piece, foundation, and scour protection. Some sources describe the support structure as comprising the tower and foundation, with the foundation extending from the water level downward. DNV further divides the structure into the support structure (from seabed to nacelle) and the foundation (extending below the seabed) [7–9]. Initially, DNV's definition did not include "substructure," but they later expanded it to include this term as part of the support structure, extending from the tower's base to the foundation. The terminology evolved to encompass the tower, substructure, and foundation under the "support structure" umbrella. For clarity, "substructure" typically refers to the section between the tower's lower part and the seabed, while "foundation" denotes the part embedded in and directly contacting the soil below the seabed. These varying definitions highlight the complexity and evolving nature of offshore wind technology. Standardising terminology is crucial for effective communication among industry stakeholders, ensuring consistent understanding in project planning, engineering, and regulatory compliance [7]. As the offshore wind sector continues to grow and innovate, precise language becomes increasingly important for coordinating efforts across different aspects of wind farm development, from design and construction to maintenance and decommissioning. This standardisation facilitates better collaboration between engineers, manufacturers, regulators, and operators, ultimately contributing to the worldwide efficient and sustainable expansion of offshore wind energy capacity [8,10].

Offshore wind's current decommissioning practices, primarily partial removal of pile foundations, risk long-term seabed availability and sustainable development. New methods for complete removal with minimal environmental impact are crucial. Europe, leading the global offshore market for three decades in technology and capacity, installed the world's first turbine and demonstration farm. Thus, it is expected to pioneer large-scale decommissioning, with some small-scale projects already completed. This focus on Europe stems from its industry leadership and imminent decommissioning needs. Developing effective, environmentally friendly decommissioning strategies are vital for the industry's future, ensuring continued growth while preserving marine ecosystems and maximising available seabed for future renewable energy projects. The challenges faced in Europe will likely provide valuable insights and solutions applicable to other regions as the global offshore wind sector matures and faces similar decommissioning issues in the coming decades [8–10].

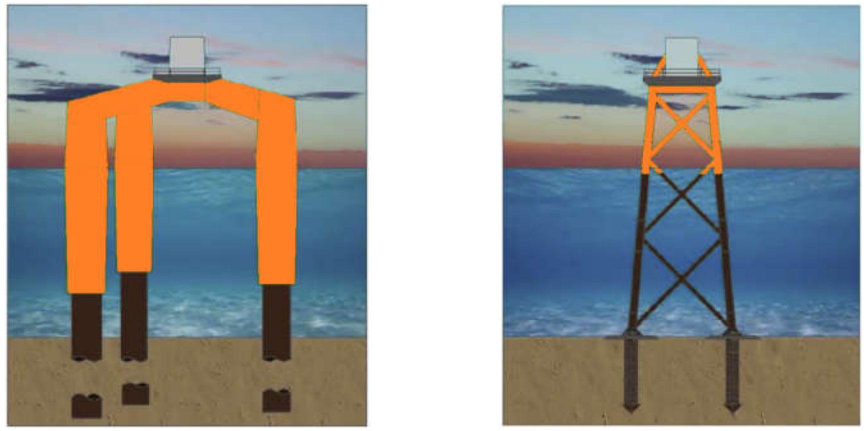
This review paper aims to address this gap by conducting a comprehensive review of state-of-the-art extraction applications for mono-pile foundations recently tested in industry and academia, including vibro-extraction and hydraulic pressure methods. Mechanics of extraction theory will be addressed across industries to identify baseline factors influencing extraction forces, such as effective soil and object weight, soil resistance along the failure surface, adhesion force, and soil suction force. This will synthesise cutting-edge research and industry practices to provide a foundation for developing sustainable decommissioning strategies for offshore wind pile foundations. With defining common offshore wind substructure and foundation types and presenting their latest share in the European offshore wind market, decommissioning will occur on a large scale for pile foundations, mainly mono-pile structures. A mono-pile is a single, large-diameter pile foundation directly supporting the wind turbine structure. In contrast, tripod, tri-pile, and jacket structures are supported by multiple smaller-diameter pile foundations at their leg positions, regardless of essential selection factors for substructure types, such as seabed condition and water depth. Although tripod, tri-pile, and jacket structures are all mounted on pile foundations, they differ in the scales (e.g., diameter) and numbers of piles due to their structural design. The insights gained will support the offshore wind industry in overcoming critical end-of-life challenges and enable long-term growth while minimising environmental impacts.

2. Fixed Offshore Wind Substructures

2.1. Mono-Pile Structure

The mono-pile foundation, consisting of a pile and often a transition piece, supports offshore wind turbine towers. It is a single, rigid, hollow steel cylinder with diameters exceeding 10 m. Mono-piles dominate the industry due to their cost-effectiveness and simple manufacturing and installation processes. Figure 1a shows a schematic view of a mono-pile structure. Fabrication involves rolling steel plates into cans and conical shapes, which are then welded to form tubular segments. These segments are joined to create one long cylindrical pipe. Installation methods depend on seabed conditions: driving through vibration or hammering in sand, clay, or chalk; drilling or boring in rocky strata. Mono-piles are primarily used in shallow waters up to 40 m deep, which could be seen as a limitation. However, their prevalence in the industry underscores their efficiency and reliability [8,11]. As offshore wind farms expand into deeper waters, innovations in mono-pile design and installation techniques continue to evolve, potentially extending their viable depth range. The mono-pile's simplicity contributes to its widespread use but also presents challenges for decommissioning. As the offshore wind industry matures, developing effective removal strategies for these structures will become increasingly important to ensure sustainable long-term development and minimise environmental impacts on marine ecosystems [7,10].

(**a**) (**b**)



(**c**) (**d**)

Figure 1. A schematic view of offshore wind fixed-steel substructures: (**a**) mono-pile, (**b**) tripod, (**c**) tri-pile, and (**d**) jacket.

2.2. Tri-Pod Structure

The tripod foundation consists of three steel cylindrical legs forming a wide base, with a central vertical shaft for tower transition [7,10], Figure 1b. This steel substructure features a single shaft emerging from sea level, branching into three legs anchored to the seabed in an equilateral triangle. Pile sleeves at the leg end, either vertical or inclined, secure the structure to the seabed [8,9,12]. Tripod pile foundations are smaller than mono-piles, ranging from 0.8 to 2.5 m in diameter [13,14]. For example, Germany's Alpha Ventus wind farm uses tripods with 2.48 m diameter piles for six of its twelve turbines [15]. Installation methods for tripod piles mirror those of mono-piles, involving driving or drilling [14]. Designed for intermediate to deep waters, tripods can be installed at depths up to 50 m. This extended depth range gives tripods an advantage over mono-piles in certain offshore environments. The tripod design offers enhanced stability in deeper waters [16,17], requiring less material than a mono-pile of equivalent depth capacity [18,19]. As offshore wind farms expand into deeper waters, tripod foundations may see increased adoption, balancing the structural requirements of larger turbines with the need for cost-effective, stable foundations in challenging marine environments.

2.3. Tri-Pile Structure

The tri-pile, a recent innovation in offshore wind substructures, first appeared in the Hooskiel prototype project (now decommissioned) and later in Germany's Bard Offshore 1 wind farm in 2008 and 2013 [20–22]. This design features a tripod-like cross-transition piece anchored to the seabed by three tubular steel piles arranged in an equilateral triangle, as depicted in Figure 1c, [23–25]. While similar to the tripod structure, the tri-pile differs in several key aspects: the shape of the transition piece, the location of the pile tops, and the diameter of the piles. In tri-pile structures, the pile tops are positioned above sea level [26,27], unlike tripods, where they remain below the seabed [12]. Tri-pile foundations typically have larger diameters, around 3.9 m, compared to tripod structures [24]. Despite these differences, both designs are suitable for water depths up to 50 m. The tri-pile represents an alternative approach to the tripod design, offering a unique solution for offshore wind turbine foundations in moderate water depths, balancing structural integrity with installation efficiency.

2.4. Jacket Structure

The jacket, also known as a space-frame or truss tower, is a sophisticated offshore wind substructure comprising three or four legs interconnected by welded bracings

[10,12]. This design utilises small-diameter circular steel tubes extending from the seabed to above the water level, Figure 1d. At its apex, the jacket features a large, centralised steel tube transition piece to support the wind turbine tower [10]. Anchoring methods for jackets include pile foundations, sleeves, or suction buckets. However, suction buckets are often excluded from consideration due to their full-removal decommissioning strategy, which involves pressure-based extraction. Jacket and tripod structures share similar pile foundation diameters, ranging from 0.8 m to 2.4 m. Notable examples include the Beatrice wind farm (588 MW) with 336 piles (2.2 m diameter) across 84 jackets and Alpha Ventus (60 MW) with 24 piles (1.8 m diameter) supporting six jackets. Designed for deeper waters, jacket structures are suitable for depths up to 60 m, offering a robust solution for offshore wind installations in challenging marine environments [15,28].

Pile foundations for offshore wind substructures employ two main installation methods: pre-piling and post-piling. The choice depends largely on the substructure leg design. Pre-piling, or preinstalled piling, involves securing pile foundations into the seabed first. A pile installation frame maintains precise centre-to-centre distances matching the jacket structure legs. After installation, the substructure legs are positioned onto the piles and secured with grout [28,29]. This method debuted with the Alpha Ventus wind farm's jacket structures [15,30]. Conversely, post-piling follows the conventional approach used in tripod structures. This method installs pile foundations within the substructure's pile sleeves after the main structure is in place. Both techniques offer unique advantages, with pre-piling allowing for more precise positioning and potentially faster installation, while post-piling provides flexibility in adjusting to seabed conditions during the installation process. Recent studies have advanced our understanding of pile foundations' behaviour under various operational conditions, including seismic response, dynamic loading, and structural performance [31–34].

The available substructure and foundation types (current and future) fall under two categories: fixed (or so-called bottom mounted) or floating support structures, as presented in Table 1.

Table 1. Summarises substructure and foundation types.

Fixed-Support Structure		**Floating-Support Structure**	
Substructure	**Foundation**	**Substructure**	**Foundation**
Gravity-based	Gravity-based	Tension leg platform (TLP)	Anchor
Monopile	Suction caisson/bucket	Semi-submersible	
Jacket	Pile	Spar	
Tripod		Barge	
Tri-pile			

Table 2 shows water depth ranges for offshore wind fixed substructures. According to WindEurope statistics for 2022, there are 6312 installed substructures for turbines with and without grid connection [35]. Fixed and floating offshore wind structures represent 99.36% (6272) and 0.38% (24), respectively, while other unspecified substructures represent 0.25% (16). The most commonly installed substructure is the mono-pile, accounting for 79.7% (5001), followed by the jacket with 11.06% (694), gravity base with 5.9% (371), tripod 2% (126), and tri-pile 1.27% (80). Floating semi-submersible, spar, and barge account for 0.375% (9), 0.58% (14), and 0.041% (1), respectively.

Table 2. The water depth ranges of most fixed offshore wind substructures.

Structure	
Gravity-based	0–30 m
Monopile	0 to 40 m
Tripod	10 to 50 m

Jacket	5 to 60 m

With defining common offshore wind substructure and foundation types and presenting their latest share in the European offshore wind market, decommissioning will occur on a large scale for pile foundations, mainly mono-pile structures. Mono-pile, tripod, tri-pile, and jacket structures penetrate the seabed and mount on pile foundations, regardless of essential selection factors for substructure types, such as seabed condition and water depth.

3. Offshore Wind End-of-Life Scenarios

Offshore wind farms face three primary end-of-life scenarios: life extension, repowering (either full or partial), and decommissioning. Although these terms are sometimes used interchangeably in the literature, it is important to note that decommissioning stands apart from the others [36,37]. The confusion often arises from the similar objectives of repowering, life extension, and refurbishment, all of which aim to prolong a wind farm's operational lifespan beyond its original design life, regardless of the extension period. Decommissioning, in contrast, involves the permanent shutdown and subsequent removal of the installed structures. To address this ambiguity and improve clarity, it is essential to establish a standardised framework that clearly differentiates between repowering and life extension strategies, independent of their financial implications or investment requirements [38,39]. By creating this distinction, industry stakeholders can gain a more comprehensive understanding of the available options for ageing offshore wind installations. This enhanced clarity facilitates more informed decision-making processes, allowing for operators to optimise the value of their assets throughout their entire lifecycle. Moreover, a well-defined set of end-of-life scenarios enables better long-term planning, potentially leading to more sustainable and cost-effective management of offshore wind infrastructure as the industry continues to mature and evolve.

Life extension in offshore wind farms aims to prolong turbine operation beyond its intended lifespan through minor repairs and maintenance. This process hinges on comprehensive assessments, both analytical and on-site, collectively known as life-extension assessments. These evaluations, conducted in the final years of operational life, examine all components from rotor to foundation to determine the turbine's current condition. DNV emphasises the need for periodic assessments throughout the project lifecycle to effectively extend a wind turbine's lifespan [37,40]. These ongoing evaluations inform and enhance maintenance strategies. The feasibility of life extension primarily depends on structural safety, operational quality, and the management of maintenance and inspection activities [41]. When deemed viable, life extension typically prolongs operational life by 5 to 10 years, representing a 25% [42] to 50% [37] increase over the average certified lifespan of 20 years. This approach allows operators to maximise asset value while ensuring continued safe and efficient operation. The life extension process requires a meticulous balance of technical assessment, risk management, and economic considerations. By carefully evaluating each turbine's condition and potential, wind farm operators can make informed decisions about extending operational life, potentially improving the overall economics of offshore wind energy production.

3.1. Repowering

Repowering and new projects are crucial for meeting Europe's future renewable electricity generation targets [38]. This strategy offers wind farms a second life by upgrading old components with next-generation, high-output technology. Repowering comes in two forms: partial and full. Partial repowering involves upgrading specific superstructure components while retaining the tower, substructure, and cables. This may include replacing gearboxes, rotors, and drivetrains with more efficient versions. Some sources also consider tower upgrades as part of partial repowering [43,44]. Full repowering, in contrast, entails replacing the entire superstructure and cabling, including the turbine, tower, and array cables. This comprehensive approach may also involve installing larger foundations to support more powerful turbines. However, major electrical infrastructure such as substations and export cables typically remain unchanged. Both repowering strategies aim to enhance wind farm efficiency and output, extending operational life while leveraging technological advancements. This approach allows operators to maximise energy production from existing sites, contributing significantly to renewable energy goals.

Repowering strategies significantly enhance wind farm capacity. Based on analyses of 60 onshore repowering projects, partial repowering can more than double a wind farm's capacity, while full repowering can quadruple it [45]. However, full repowering often reduces turbine numbers by over 30% due to decommissioning older units. The world's first offshore wind farm repowering occurred at Bockstigen in Sweden [37,45]. Commissioned in 1998 with five 0.55 MW turbines, Bockstigen underwent partial repowering in 2018 after two decades of operation. The project replaced blades, nacelles, and control systems with refurbished V47–660 kW turbines while retaining original foundations, towers, and cables [46,47]. This partial repowering extended Bockstigen's life expectancy by 15 years and increased its capacity from 2.75 MW to 3.3 MW. Interestingly, Bockstigen's initial plan was to decommission the existing turbines and install ten new 4 or 5 MW units. The decision to partially repower instead demonstrates the flexibility and cost-effectiveness of this approach. This pioneering project highlights the potential of repowering in the offshore wind sector. By upgrading key components while utilising existing infrastructure, operators can significantly extend wind farm lifespans and increase energy output, contributing to renewable energy targets more efficiently.

The decision to repower offshore wind farms hinges on various factors, including regulatory frameworks, project scale, and site-specific characteristics [37]. Additionally, wholesale electricity market trends, expiring lease or maintenance contracts, and public support play crucial roles in shaping repowering strategies [38,45]. In the UK, the Crown Estate typically grants 40- to 50-year site leases for offshore wind farms, accommodating two full operational lifecycles. Examples include Thanet and Lincs (40 years) and London Array and Greater Gabbard (50 years) [48]. The latest Round 4 leasing has extended this duration to 60 years, offering even greater flexibility. While repowering decisions are often considered at mid-life, around 15 years into operation (assuming an initial life extension), some operators may opt for earlier repowering, even as soon as nine years into operation [45]. This proactive approach is driven by potential economic benefits and the desire to maximise resource utilisation at prime locations using improved technologies [43]. Key motivators for early repowering include capitalising on sites with superior wind resources and leveraging turbine design and efficiency advancements. This strategy allows operators to optimise energy production and financial returns while extending the productive life of established offshore wind sites.

Repowering often emerges as a more appealing end-of-life scenario than decommissioning for offshore wind farms, primarily due to the continued utilisation of prime wind resource locations. However, its feasibility depends on various factors, and decommissioning may sometimes be the only viable option. The Yttre Stengrund wind farm in Sweden exemplifies this reality. Operational since 2001 with five 2 MW turbines totalling 10 MW capacity, it became the world's first decommissioned offshore wind farm after 15 years of service. The decommissioning process spanned from Q4 2015 to Q3 2016 [49]. Despite having permission to repower, Yttre Stengrund faced insurmountable challenges. The turbines were early models with limited production (only 50 units manufactured) [50], making spare parts procurement and obsolescence management increasingly complex. This case underscores that repowering is not always feasible, even when desired. It is crucial to recognise that while life extension, repowering, or hybrid approaches can prolong a wind farm's operational life, they do not eliminate the inevitability of eventual decommissioning. As illustrated in Figure 2, decommissioning remains the final phase in any offshore wind project's lifecycle, regardless of interim strategies employed to extend its productive years.

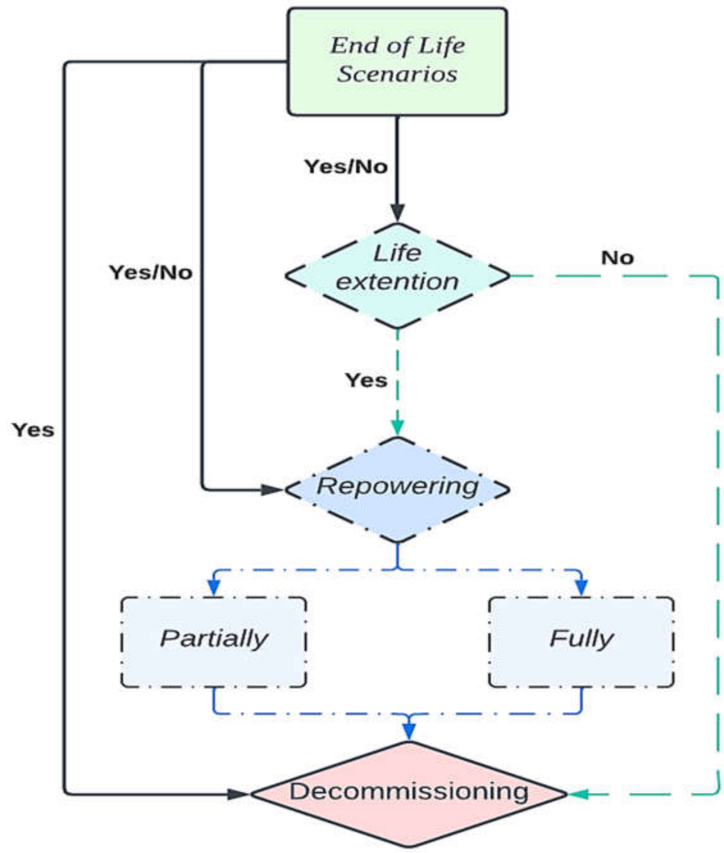


Figure 2. The potential sequence of end-of-life scenarios.

3.2. Decommissioning

Decommissioning marks the final phase of a project's life cycle, aiming to restore the site to its original state as much as possible and eliminate any risks to society or the environment created during the project's existence. In the offshore wind sector, obtaining project approval requires submitting an initial decommissioning plan before construction begins. This plan outlines the decommissioning process and its feasibility and ensures adequate funding is allocated to cover associated costs. Figure 3 illustrates a simple sequence of OWF decommissioning phases adopted from the publicly published decommissioning programmes. As the project progresses through installation and operation, the initial plan evolves into a more detailed one through periodic reviews and modifications. These updates account for changes in regulations, technology, costs, market conditions, and international standards. This ongoing refinement process helps mitigate uncertainties and potential issues that may arise when decommissioning actually begins [51].

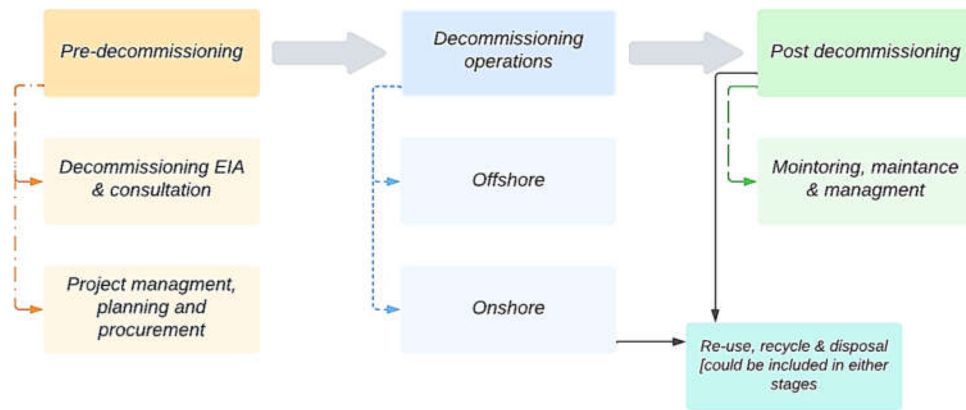


Figure 3. Break-down of the offshore-wind-farm-decommissioning process stages.

The UK Energy Act 2004, under section 108, mandates these reviews and revisions of decommissioning programmes, underscoring their importance [52]. The rationale behind this approach is to ensure that decommissioning measures remain relevant and effective, as conditions may change significantly between the project's inception and its end-of-life phase. By continually updating the plan, project owners can better prepare for the actual decommissioning process, potentially saving time, resources, and costs while minimising environmental impact. This adaptive strategy reflects the long-term nature of offshore wind projects and the need for flexible, forward-thinking approaches to their eventual dismantling and site restoration.

The decommissioning process for wind turbine superstructures is relatively straightforward, essentially reversing the installation sequence. It begins with removing the blades, followed by the nacelle and tower sections. While various methodologies may be developed for dismantling components, the overarching strategy aims to minimise offshore operations and maximise onshore work. This approach reduces safety risks, time requirements, resource utilisation, and overall offshore expenditures. Although the basic process remains unchanged, ongoing innovations in dismantling techniques continue to emerge. The focus is on efficient, safe, and cost-effective methods that prioritise conducting as much work as possible onshore, where conditions are more controlled and resources more readily available.

Decommissioning offshore wind foundations presents complex challenges, varying with foundation type and available technology. Unlike installation, foundation removal often requires different techniques, especially for pile foundations. These can be fully excavated or partially removed by cutting at or below the seabed, either internally or externally. Suction bucket foundations, however, follow a complete removal strategy, reversing the installation process by releasing and extracting through pressure application. The choice of decommissioning method depends on site-specific factors, including available vessels and equipment, foundation type, weather conditions, distance to ports, and water depth. Decommissioning has been executed for 10 offshore wind farms/turbines across Europe, with the most recent in 2022, as illustrated in Table 3.

Table 3. Summary of decommissioned offshore wind farms/turbines.

OWF Name	Country	Comm. Year	Decom. Year	Operational Years	Total Cap. (MW)	Foun. [Turb. No]	Area (km^2)
Nogersund	Sweden	1990	2007	14 [2004]	0.22	TPod	0.25
Vindeby	Denmark	1991	2017	26	4.95	GBS	0.45
Lely	Netherlands	1994	2016	22	2	MP	0.04
Irene Vorrink	Netherlands	1996	2022	26	17 [16.8]	MP	0.4
Blyth	UK	2000	2019	13 [2013]	4	MP	0.4
Utgrunden 1	Sweden	2000	2018	18	10.5	MP	0.45
Yttre Strengrund	Sweden	2001	2015	14	10	MP [drilled]	0.06
Hooksiel	Germany	2008	2016	8	5	TPile	N/A
Robin Rigg	UK	2010	2015	-	6	MP	N/A
WindFloat	Portugal	2011	2016	6	2	Floating	3.11

These projects have adapted experiences from the offshore oil and gas sector and generated valuable industry-specific knowledge and experience. However, the offshore wind sector requires several decades of experience to make truly accurate and precise decommissioning decisions. This is partly because the decommissioned projects thus far have been relatively small-scale compared to currently operational farms, particularly in terms of turbine numbers, specifications, water depth, and distance from shore. As the industry matures, it will likely develop more sophisticated and efficient decommissioning strategies. A growing body will inform those of practical experience, technological advancements, and a deeper understanding of different decommissioning approaches' long-term environmental and economic impacts. This evolution will be crucial as larger, more complex offshore wind farms reach the end of their operational lives in the coming decades.

The offshore wind industry is approaching a significant milestone, with many operational wind farms nearing the end of their designed lifespans. Consequently, from late 2020 onwards, there has been an anticipated surge in decommissioning activities. However, the implementation of life extension and repowering strategies could potentially defer this process until 2046. The results derived from the analysis of these two scenarios, in terms of time and volume (capacity, farms, and turbines), are displayed in Figures 4 and 5. This study analysed wind farms commissioned after the Middelgrunden project, which was chosen as a baseline due to its status as the first large-scale installation. The research excluded pilot projects and focused on EU countries with the highest-installed wind capacities: the UK, Germany, Netherlands, Denmark, and Belgium. Data were primarily sourced from 4C offshore and processed using relevant software. Two scenarios were considered for the end-of-life timeline:

- The default option is decommissioning after 20 years of operation.
- An extended timeline: decommissioning after 45 years, comprising 20 years of initial operation, 5 years of life extension, and 20 years of repowering.

The analysis provides insights into the projected decommissioning volume in terms of capacity, number of farms, and turbine count under these scenarios. This information is crucial for industry planning and resource allocation. As the offshore wind sector matures, the approach to end-of-life management will likely evolve, influenced by technological advancements, economic factors, and environmental considerations. This study aims to provide a foundation for understanding and preparing for the impending wave of decommissioning activities in the offshore wind industry.

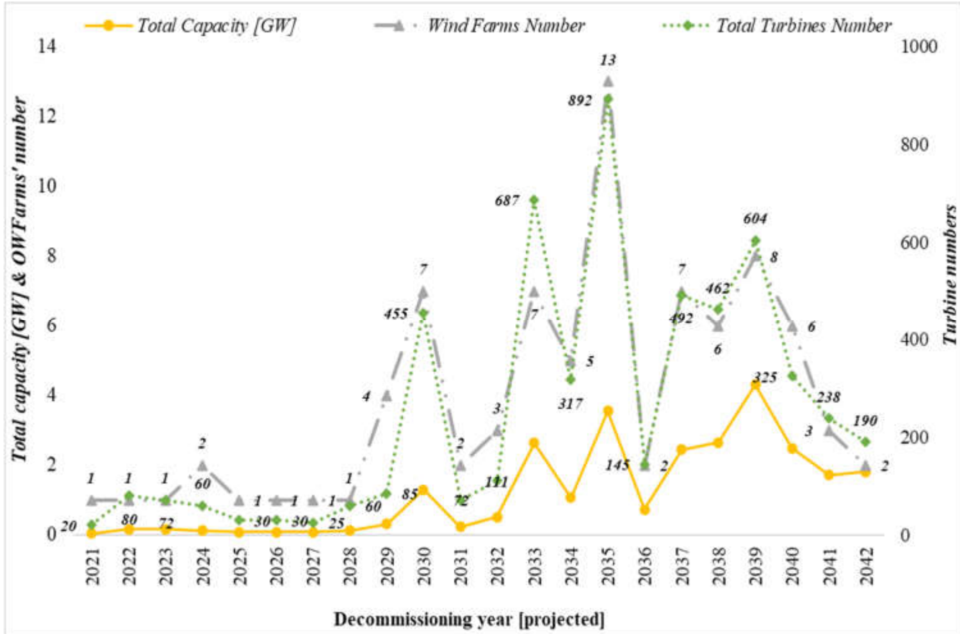


Figure 4. The capacities and the number of offshore wind farms and their turbines projected for decommissioning, the default option, over the next two decades.

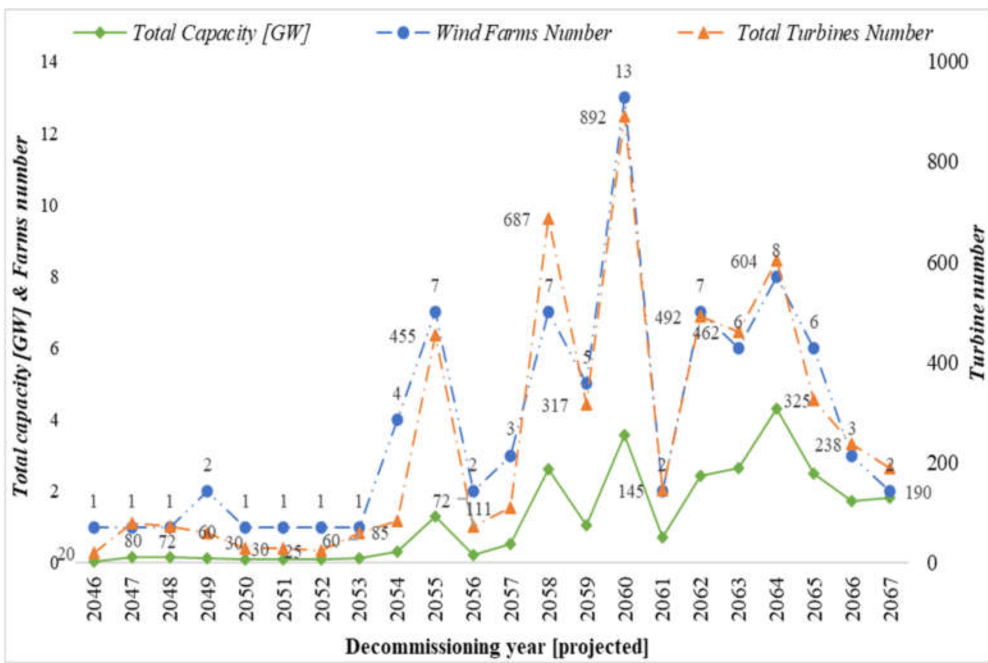


Figure 5. The time that the decommissioning will occur, following the adoption of life extension and repowering scenarios.

4. Offshore-Wind-Pile-Foundations-Decommissioning Operations

The analysis in Section 3 reveals that operational offshore wind farms occupy over 4000 km² across Europe, with the UK leading at 2398 km², followed by Germany, Denmark, The Netherlands, and Belgium. The potential for reusing or repurposing these areas for future sustainable development hinges largely on the decommissioning strategies employed for existing foundations. To gauge the industry's long-term outlook, experts in offshore oil and gas and wind sectors were asked: "What technologies or methodologies, whether existing, proposed, or new, will be developed for decommissioning offshore wind single fixed-steel pile foundations in the coming years?" This question aims to explore innovative approaches that could shape the future of offshore wind farm decommissioning, potentially influencing land use and sustainable development strategies in marine environments.

Expert responses, illustrated in Figure 6, indicate a preference for developing new decommissioning methods like vertical excavation and explosive cutting while enhancing existing techniques. Notably, 34% of experts equally favoured internal pile-cutting and -extraction methodologies. Despite the various methods proposed, the industry is likely to prioritise strategies that are cost-effective, user-friendly, and minimise disruption to marine environments. This approach reflects a balance between innovation and practicality, as the sector seeks efficient and environmentally responsible ways to decommission offshore wind foundations.

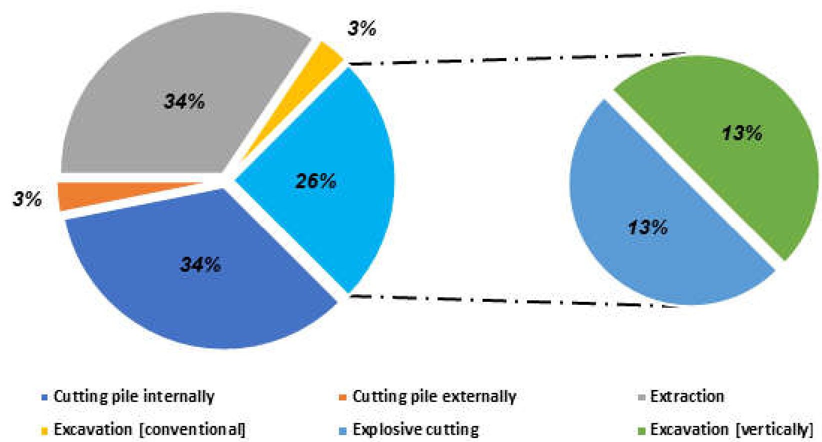


Figure 6. The percentage of OW-foundations-decommissioning methodologies supported by offshore oil and gas and wind industry experts.

4.1. Partial Removal Strategy

The industry consensus favours partial removal as the preferred decommissioning strategy for offshore wind foundations, as evidenced by published decommissioning programmes (Table 4). This preference stems from its reduced site disturbance, practicality, commercial feasibility, and safety advantages. The strategy involves cutting the foundation at or below the seabed, leaving the lower portion in place. The process comprises excavation, cutting, and lifting, regardless of the specific methodology employed. However, the apparent simplicity of this approach is complicated by site-specific factors, particularly soil conditions, which influence cutting depths and excavation requirements. For instance, cutting depths range from 1 to 2 m below the seabed for foundations in hard rock to 5–10 m for those in sandbanks [53]. The latter deeper cut accounts for potential sand movement over time that could expose remaining structures. As a standard practice, the initial excavation depth is set at 1 m below the intended cutting depth, regardless of seabed composition [54,55]. These variations highlight the intricate relationship between cutting methodology, depth, and seabed conditions in determining appropriate excavation methods and equipment. Each site presents unique challenges, requiring tailored approaches to ensure effective and safe partial removal. This nuanced reality underscores the importance of thorough site assessment and flexible planning in offshore wind farm decommissioning. While partial removal offers several advantages, its implementation demands careful consideration of local conditions to achieve optimal results in terms of environmental impact, cost-effectiveness, and long-term site integrity.

Table 4. Summarises the proposed decommissioning strategies and methodologies for OW foundations.

OW Foundations Decommissioning				
Wind farm name	Lincs	Sheringham Shoal	Greater Gabbard	Burbo Bank Extension
Decommissioning Strategy	Partial removal	Partial removal	Partial removal	Partial removal
Cutting method	Internally	Internally	Externally	-
Excavation method—depth(m)	Internally—2 m	Internally—2 m	Externally—2 m	Internally and externally 1.5 m
Cutting depth (m)	1m (initial)	1m (initial)	1m (initial)	1m (initial)

Internal pile cutting is preferred over external cutting in the partial-removal process despite both requiring excavation. This preference stems from the reduced seabed damage caused by internal cutting. External cutting necessitates a wider excavation area, increasing by 2 m in diameter for every 1 m of depth. This larger excavation footprint leads to higher costs, increased personnel risks, and greater environmental impact. Excavations exceeding 1 m depth are considered particularly damaging and intrusive to the seabed environment. To facilitate the separation of the pile from the surrounding soil, partial-removal methods may incorporate techniques like vibratory hammering to overcome frictional forces at the soil–structure interface. Table 5 provides a detailed overview of these partial-removal methodologies [54–58].

Table 5. Summarise the differences between the partial-removal strategy methodologies.

Parameters	**Partial Removal Methodologies**	
	Cutting Internally	**Cutting Externally**
Soil excavation method	Inside the pile	Around/outside the pile
Soil excavation technique	Drilling/milling OR high-pressure water jetting (HPWJ)	Excavate
Soil excavation equipment	Drill string (drill pipe, bottom hole assembly and drill or mill bit)	Subsea/seabed dredgers, supported by ROV for restricted area
Cutting technique	[Abrasive] water jetting (WJ)	[Abrasive] diamond wire cutting (DWC)
Cutting deployment	Lowering from the vessel	ROV or sea crawler

4.2. Full Removal Strategy

4.2.1. Excavation

The industry has proposed excavation as a full-removal method for offshore wind foundations, expanding on the concept used in partial-removal strategies but on a larger scale. This approach creates a truncated cone shape, with the excavation diameter increasing by 2 m for every 1 m of depth. However, published decommissioning programmes provide limited information on this method, suggesting it may not be the industry's preferred option. The reluctance to adopt full excavation stems from its potential to cause significant environmental damage, high risks, and substantial costs due to the need for specialised equipment over extended periods. The extensive excavation required along the entire pile foundation depth is particularly concerning. Despite these drawbacks, full removal through excavation offers advantages in terms of sustainable development and material reuse compared to partial-removal methods. This presents a complex trade-off between environmental impact, cost, and long-term sustainability that the industry must carefully consider.

4.2.2. Extraction

Extraction and reuse of piles are common practices in onshore environments, particularly for temporary structures. These methods, including pulling, vibration, and rotation, could become increasingly relevant for offshore wind decommissioning in the future [59]. Extraction offers several advantages over the currently preferred partial-removal strategy:

- Full recycling: steel pile foundations are 100% recyclable, supporting a circular economy approach.
- Reduced long-term costs: elimination of post-decommissioning monitoring and maintenance of in situ structures.
- Environmental benefits: potentially less disruptive to the marine environment in the long term.

The current industry strategy designs structures with partial removal in mind. However, extraction could prove more beneficial and profitable as the industry evolves. It would eliminate the need for long-term monitoring surveys, which typically occur immediately after decommissioning, annually for two years, and at five- and ten-year intervals thereafter [55]. Figure 7 provides a comparative overview of the processes involved in partial-removal methodologies versus extraction. This comparison highlights the potential streamlining of decommissioning operations and reduction in long-term commitments that extraction could offer to the offshore wind industry.

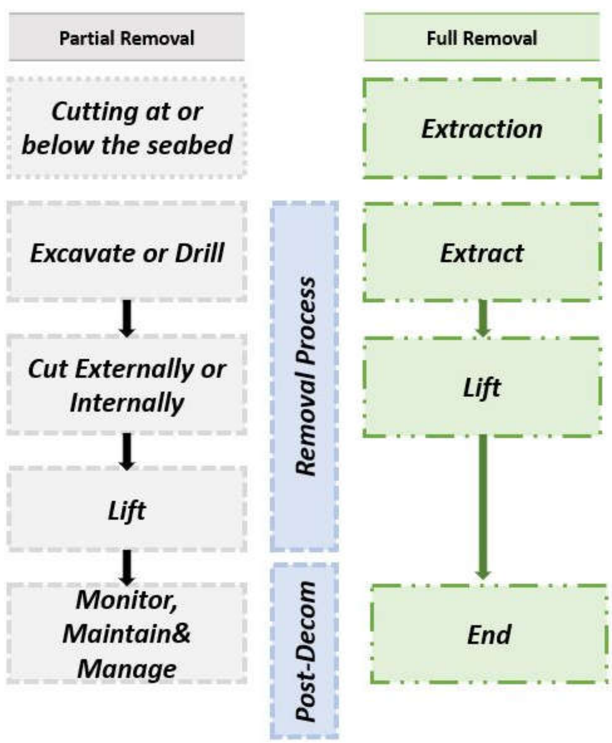


Figure 7. A simplified comparison of activities for partial-removal and extraction methodologies.

Pile extraction for offshore wind foundations has progressed from experimental testing to successful small-scale implementation. A notable example is the Lely wind farm in Denmark, the first to undergo full-removal decommissioning [60,61]. This 2 MW capacity farm, consisting of four 0.5 MW turbines on mono-pile foundations, was operational from 1994 to 2016. The Dieseko Group executed the decommissioning using vibration extraction techniques. They employed a vibro-hammer (PVE 500M) to remove the 26 m-long pile foundations, which had diameters ranging from 3.2 to 3.7 m. The extraction process was remarkably efficient, taking only 180 min, or approximately 45 min per foundation.

This successful operation demonstrates the potential viability and efficiency of full-removal strategies for offshore wind farm decommissioning, paving the way for future applications of this technique on larger scales.

Recent experimental research has explored innovative extraction techniques for offshore wind foundations. The Hydraulic Pile Extraction Scale Tests (HyPE-ST) project, conducted at Deltares' water–soil flume facility, investigated hydraulic extraction using water pressure [62]. The experimental campaign was conducted in four different soil conditions: dense sand, medium dense sand, clay, and layered soil strata (dense sand and clay). The installation method that was utilised for the piles was impact driving. The extraction method involves sealing the pile's top and pressurising its interior void, forcing the pile upwards. Experiments using 1:20 and 1:30 scale models demonstrated the feasibility of this hydraulic pressure extraction technique [63]. Furthermore, the tests' results showed that the type and configuration of the soil highly influence the breakout pressure. Another significant development comes from the Floating Offshore Installation (FOX) project for XXL wind turbines. This initiative tested novel installation methods for various turbine components. A mono-pile foundation was installed using an innovative approach as part of the Slip Joining Offshore Research (SJOR) project in 2018 [64]. The method employed a vibro-lifting tool on a dynamically positioned floating vessel, eliminating the need for a gripper frame or impact hammer. Notably, upon completion of the FOX project, the mono-pile installation process was successfully reversed for removal [65]. This demonstration highlights the potential for developing installation techniques that can be efficiently reversed for decommissioning, potentially streamlining the entire lifecycle process of offshore wind structures. These experimental projects showcase the ongoing innovation in offshore wind foundation installation and removal techniques, pointing towards more efficient and potentially less disruptive methods for future decommissioning operations. Developing reversible techniques necessitates a fundamental shift in design philosophy. Instead of focusing solely on optimising designs for installation and operation, there must be an emphasis on design for decommissioning. Design for decommissioning would ensure that offshore wind foundations are built with eventual removal in mind, allowing for a more efficient and sustainable decommissioning process. However, this introduces challenges in maintaining structural integrity throughout the wind farm's lifecycle. The design must balance ensuring structural robustness during operation and facilitating ease of removal, allowing for decommissioning without compromising the foundation's integrity or causing significant environmental impact.

The industry should first focus on defining and understanding the key parameters influencing the extraction process to ensure the scalability and technical feasibility of novel extraction methods. This involves developing a comprehensive theory of extraction, which can then be validated through experimental campaigns conducted at different scales. Numerical models should support these experiments to simulate various conditions, such as soil behaviour structural responses. By integrating both experimental and computational approaches, the industry can optimise the extraction methods and ensure they are technically feasible and scalable for implementation in real life.

5. Decommissioning Considerations

During the operation and maintenance phase, offshore wind farms may undergo life extension, repowering, or both as end-of-life scenarios. However, decommissioning ultimately becomes inevitable after these options are exhausted. Figure 8 illustrates the factors influencing the adoption of each end-of-life scenario. The long-term sustainability of offshore wind development significantly depends on its decommissioning approach, especially regarding foundations. The chosen decommissioning strategy and method for foundations have a substantial impact on future seabed availability. Figures 9 and 10 demonstrate how the industry's currently preferred strategy of partial removal affects fixed foundations and seabed use. The preference for partial removal over full removal (excavation) stems from its lower risk, reduced environmental impact, and shorter removal duration. However, this approach may have long-term implications for seabed utilisation and the industry's sustainable growth. As the offshore wind sector expands, balancing immediate operational benefits with long-term environmental and economic considerations becomes increasingly crucial. This balance will play a vital role in shaping the future of offshore wind energy and its impact on marine ecosystems.

Introducing a novel extraction methodology for the full removal of offshore wind foundations could revolutionise decommissioning practices, potentially offering significant benefits in terms of environmental impact, duration, and cost. This approach contrasts sharply with the current industry preference for partial-removal strategies. While less disruptive in the short term, partial removal poses long-term challenges for seabed utilisation. It could render areas partially inaccessible for future development, creating a scenario reminiscent of onshore wind turbine blade landfills, as illustrated in Figure 11.

Figures 9 and 10 provide a comparative analysis of how partial removal and the proposed novel extraction method impact seabed availability. These illustrations highlight the potential long-term consequences of different decommissioning strategies on marine spatial planning and future offshore wind development. For simplicity, Figure 9b uses the North Seas as a case study, assuming the entire seabed is dedicated to offshore wind development without maritime spatial-planning exclusions. This hypothetical scenario helps visualise the cumulative impact of decommissioning strategies on large-scale offshore wind deployment and future seabed utilisation. This comparison underscores the importance of considering long-term impacts when developing decommissioning strategies for offshore wind farms.

The choice of foundation removal strategy significantly influences total decommissioning expenditures (DecExs). The duration of removal activities directly affects vessel on-site time and associated costs, a major component of overall DecEx; [66] developed a cost and time model for OWFoundations decommissioning to define the most cost-effective strategy and methodology. The model incorporated various input parameters, including removal operation duration, vessel strategies, types and day rates, and wait-on-weather. Notably, the key factor differentiating the costs of the novel extraction method from the currently preferred partial-removal strategy is the removal operation duration. The reason was due to the number of removal activities involved.

The activities typically include internal or external excavation, cutting the pile at or below the seabed and lifting for partial removal. In contrast, the extraction method involves only extraction and lifting. Relying on the studied publicly published offshore-wind-farm-decommissioning programmes, including Lely Offshore Wind Farm, [66] estimated the average duration of novel extraction method to be 8 h, compared to 24 h for the preferred partial-removal strategy.

A crucial factor in this equation is the wait-on-weather condition, which substantially impacts removal operation duration regardless of the chosen strategy or method. This, in turn, extends vessel on-site time. Wait-on-weather (WOW), or weather downtime, occurs when adverse weather conditions, primarily wind speed and wave height, exceed the permissible operating limits of vessels for conducting offshore activities. WOW can differ considerably depending on several factors related to the wind farm, such as its location, size, and metocean data, which play pivotal roles in determining the frequency and intensity of WOW incidents. Accordingly, weather is a pivotal factor influencing the total cost, scheduling, and duration of offshore activities throughout a project's lifecycle, often leading to postponements at various project phases.

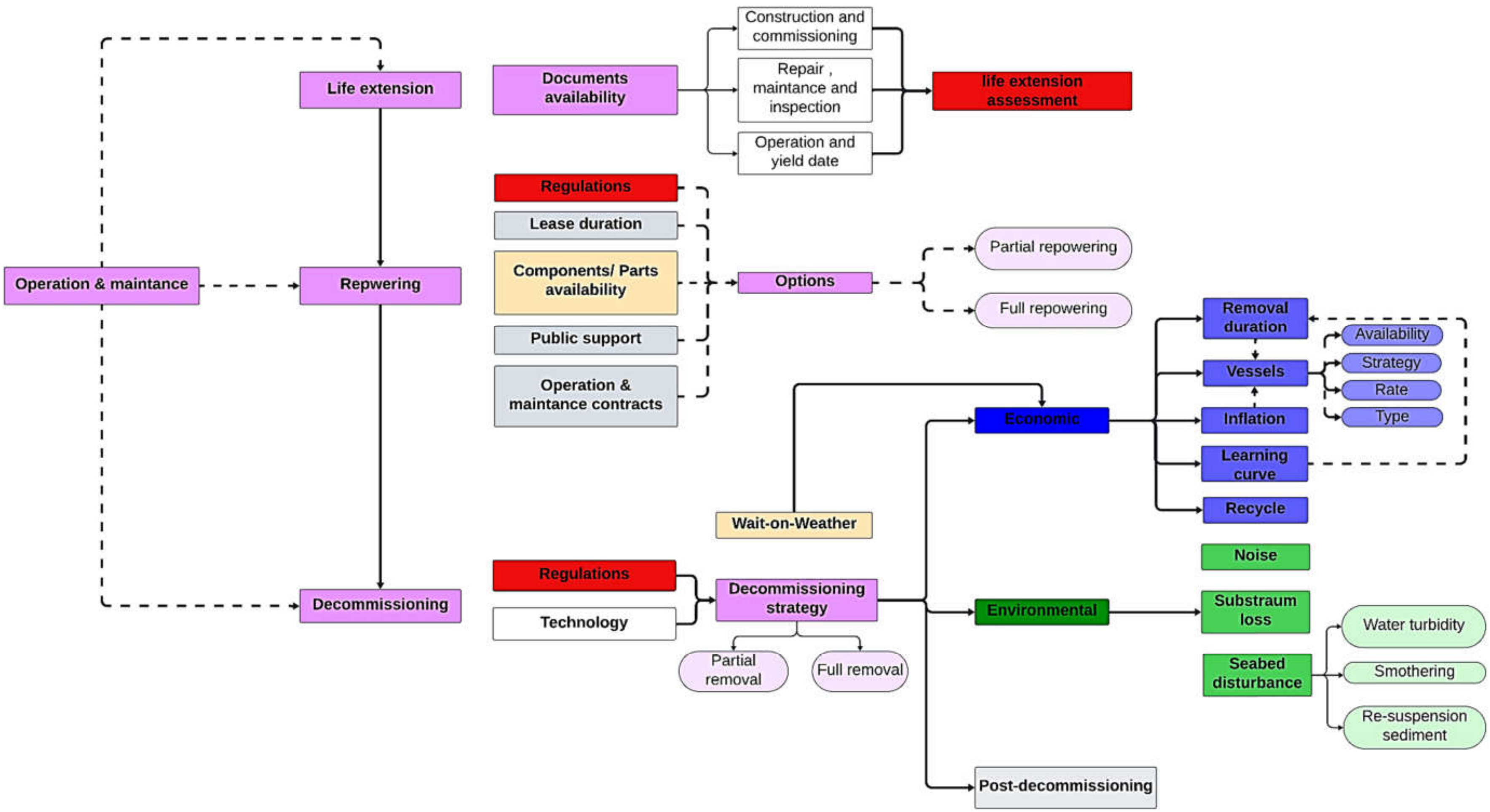
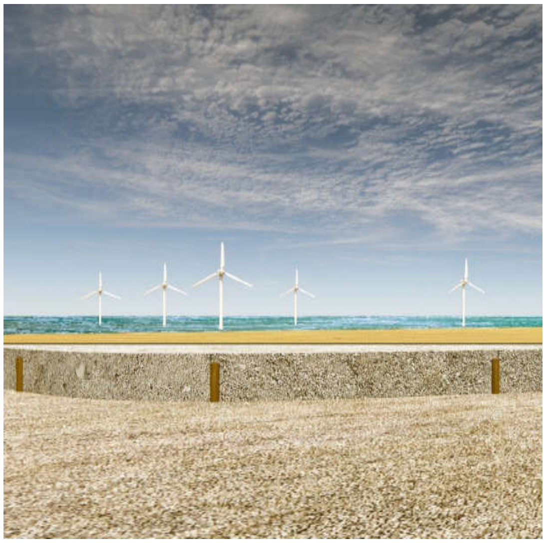
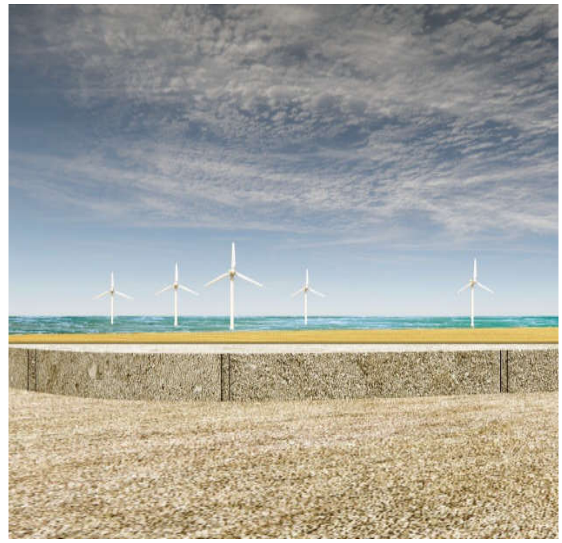


Figure 8. The impacting factors on each of the end-of-life scenarios.



(a)



(b)

Figure 9. (**a**) The industry's proposed/preferred offshore-wind-foundations-decommissioning strategy impact—partial removal—on the seabed. (**b**) Offshore wind foundations' full-removal strategy impacts the seabed.

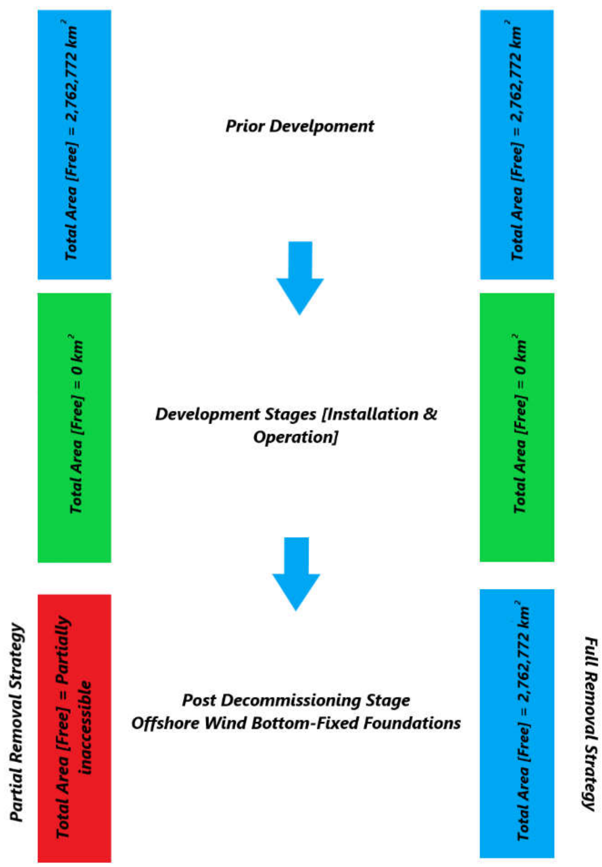


Figure 10. The impact of offshore-wind-bottom-fixed-foundations-decommissioning strategies concerning seabed availability on the industry's long-term development sustainability.

Figure 11. The impact of fabricating materials for wind turbine blades [resin/fibre glass] on decommissioning: a top view of the Casper landfill, Wyoming.

Utilising vessels with higher environmental criteria in deep- or open-sea regions can extend the operational weather window. For example, wind turbine installation vessels (WTIVs) can theoretically operate about 70–80% of the year in areas where wave heights typically reach 2 m but may exceed 3 m during certain times. In contrast, self-elevating jack-up barges, with a significant wave height range of 1.2–1.5 m, may operate only about 40% of the year or less. Moreover, not all jack-up vessels/barges operating can remain elevated on-site during extreme weather, necessitating their mobilisation to a safer location. Therefore, weather conditions are critical in offshore wind projects, affecting project cost, schedule, and duration. This emphasises the need for meticulous planning and robust decision-making to ensure project efficiency and safety.

Consequently, the wait-on-weather factor plays a critical role in vessel selection. These interconnected factors underscore the complexity of offshore wind decommissioning planning and the importance of considering multiple variables when estimating costs and timelines [66–68]. Apart from cable-removal activities, the decommissioning methodologies for offshore wind foundations and the use of vessels—particularly Jack-Ups—significantly contribute to seabed disturbance. The disturbance adversely impacts the water quality by increasing turbidity. Addressing seabed disturbance is crucial, highlighting the need to innovate and develop new decommissioning methodologies for offshore wind foundations. For instance, comparing extraction applications, vibration and force-control, force-control produces lower to no noise and vibration compared to the vibration-based extraction method. However, this does not imply that force-control will eliminate seabed disturbance; rather, it may alter the nature of the disturbance. To address seabed disturbance, the industry should implement strategies and methodologies that have a low impact, as no strategy or methodology is without any impact. In contrast, the impact caused by the legs of Jack-Up vessels when entering and exiting the seabed—whether self-propelled or barges—cannot be avoided. This is due to these vessels' essential role in decommissioning offshore wind turbines towering heights above the seabed.

The offshore wind industry is evolving its approach to decommissioning, initially focusing on recycling turbine blades instead of landfilling. This shift is expected to extend to other components, particularly fixed-steel pile foundations in offshore installations. As the industry's current proposed methods may not always be suitable, developing novel decommissioning techniques, such as complete removal through extraction, becomes increasingly crucial. In other words, the industry can extend the approach of recycling turbine blades to pile foundations by developing innovative full-removal methodologies. This would shift the focus toward "design for decommissioning" rather than solely for installation and operation. This paradigm shift would ensure that end-of-life considerations are integrated into the initial design phase, making future recycling and material recovery more efficient. Additionally, it can advocate for the formulation of independent decommissioning regulations specifically tailored to the unique requirements of offshore wind structures. These regulations would be distinct from those currently used in the oil and gas sector. This regulatory independence would allow the industry to develop more appropriate and sustainable approaches to foundation recycling, taking into account the specific characteristics and challenges of offshore wind infrastructure.

There is a pressing need for comprehensive research into both current (preferred) and innovative decommissioning strategies for offshore wind fixed-steel pile foundations. This research should encompass three key aspects:

- Engineering: exploring technical feasibility and efficiency of various removal methods.
- Environmental: assessing the ecological impact of different decommissioning approaches.
- Economic: analysing cost-effectiveness and long-term financial implications of decommissioning strategies.

By addressing these areas, the industry can develop more sustainable, efficient, and environmentally responsible decommissioning practices. This holistic approach will be vital in ensuring the long-term viability and growth of offshore wind energy while minimising its environmental footprint.

6. Summary

This critical review has examined the current landscape and future prospects of decommissioning strategies for offshore wind fixed-steel pile foundations. Decommissioning has become crucial for sustainable development as the industry matures and more wind farms approach their design life end. The review highlights that partial-removal techniques are currently preferred due to perceived lower risks and impacts. However, they may have significant long-term consequences for marine spatial planning and seabed availability. Full-removal strategies, particularly novel extraction methods, offer potential benefits in terms of complete foundation reuse, recycling, and minimised post-decommissioning monitoring. However, these methods' scalability, technical feasibility, and economic viability remain uncertain. To address these challenges and support sustainable offshore wind growth, extensive research and collaboration among industry, academia, and policymakers are essential.

Addressing these research gaps and fostering cross-sectoral collaboration can help the offshore wind industry develop holistic and sustainable decommissioning solutions. This approach will support responsible end-of-life management of existing wind farms and contribute to the overall decarbonisation of the energy sector.

As the offshore wind sector expands, decommissioning strategies for fixed-steel pile foundations will be critical in determining this renewable energy technology's long-term sustainability and social acceptance. By prioritising research, innovation, and proactive end-of-life planning, the industry can maximise the benefits of offshore wind while minimising the environmental footprint and legacy for future generations. This holistic approach will ensure offshore wind's continued growth and success as a key component of the global transition to a low-carbon economy.

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