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Original research article

Getting stakeholders aboard for offshore wind decommissioning: A qualitative study on end-of-life challenges in Belgium

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ABSTRACT

Decommissioning offshore wind farms presents significant challenges as the sector approaches the final phase of its operational lifecycle. This research examines end-of-life challenges through the perspectives of a diverse range of stakeholders, including industry, government, research, and civil society. While the study focuses on Belgian stakeholders, the challenges and solutions are expected to be relevant to similar cases. Semi-structured interviews identified 67 challenges across five end-of-life phases: planning, dismantling, transport and logistics, waste management, and monitoring site recovery. These challenges span technical, economic, environmental, social, and policy dimensions. Among them, 27 newly recognized challenges were identified. Key issues, such as composite recycling, removal legislation, port suitability, artificial reef effects, and uncertainty surrounding dismantling approaches, emerged as central concerns. These concerns were highlighted by nearly all stakeholder groups. This study addresses gaps in existing knowledge by providing comprehensive stakeholder mapping for the end-of-life phase of offshore wind farms. It incorporates stakeholder perspectives into the identification and evaluation of challenges. To validate findings, the study includes a qualitative analysis that separately examines expert stakeholders. The findings offer a detailed understanding of major concerns in offshore wind decommissioning. Recommendations include ensuring transparent grid connections, developing improved removal strategies, and adopting a more coordinated approach to transport and logistics. Waste management recommendations focus on improving blade design and addressing policy and economic issues for existing blades. The study underscores the importance of stakeholder engagement. It highlights the need for systematic involvement in end-of-life research, offering valuable insights for sustainable decommissioning practices.

1. Introduction

The introduction of offshore wind energy (OWE) in Europe started in 1991 with the installation of the first offshore wind farm (OWF) Vindeby in Denmark. By the end of 2023, offshore wind had gained momentum, with a total operational capacity of 41 GW in Europe and 34 GW in Asia [1]. Among OWF components [2], wind turbines, with a designed nominal service life of 20 to 25 years, will be the first to reach their end-of-life (EoL) [3]. Decommissioning has been limited so far, with early projects like Swedish Yttre Stengrund, Dutch Lely, and Danish Vindeby highlighting complexities [2,4]. Topham et al. [5] projected that around 1800 offshore wind turbines in Europe will reach their operational lifespan between 2020 and 2030, a number expected to rise in the subsequent decade.

In a project's concluding phase, decommissioning requires restoring the seabed to its original state by removing all OWF components [6]. The ongoing debate on full versus partial component removal encompasses various environmental and logistical aspects that require careful consideration [5–7]. Alongside decommissioning, the literature suggests life extension and repowering as alternative EoL strategies, influenced by asset conditions and legal requirements, with decommissioning often mandated by state licenses [3,8]. Despite potential legal revisions, decommissioning remains inevitable for offshore wind projects [9].

Decommissioning involves five phases: planning, dismantling,

Abbreviations: OWE, offshore wind energy; OWF, offshore wind farm; BPNS, Belgian part of the North Sea; EoL, end-of-life; SC, supply chain; QH, Quadruple Helix.

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transport and logistics, waste management, and monitoring site recovery [2,10–13,15,16]. Winkler et al. [15] highlighted that each phase comprises multiple activities, from regulatory approval to site monitoring. These diverse activities are conducted by various companies, each involving and affecting multiple stakeholders. For each of these stakeholders, different challenges may arise. A recent literature review categorized challenges across the five EoL phases into five dimensions: technical, economic, environmental, social, and policy [17]. The study identified 46 challenges, with the planning phase and the technical dimension having the highest shares. Existing literature was found to emphasize vessel availability and costs, while the research highlighted less-addressed challenges crucial for anticipated decommissioning acceleration. However, this study relied solely on peer-reviewed articles, overlooking insights from stakeholders and the public debate.

The impending EoL phase for OWE involves diverse stakeholders, yet the literature lacks a structured engagement with them. Searching for EoL and offshore wind literature for stakeholders on Web of Science yields only 13 publications, increasing to 18 when including those mentioning the supply chain (SC). Yet, only three publications focus on stakeholders at EoL. Kerkvliet & Polatidis [18] introduced a methodological framework for decommissioning OWFs, applied in a Netherlands case study with hypothetical stakeholders. Spielmann et al. [10] proposed a practical approach in Germany, integrating stakeholders, sustainability, and processes in decommissioning through surveys, workshops, and expert collaboration. Winkler et al. [15] investigated how stakeholders in the decommissioning SC address collective uncertainties through expert interviews with ten companies.

While these studies initiate stakeholder involvement in the EoL phase research for OWE, none comprehensively cover all relevant players. First, civil society stakeholders are only considered hypothetically [18]. Second, the literature oversimplifies the diverse policy landscape of offshore wind decommissioning, often neglecting involvement from various government entities with distinct preferences. While one study includes only municipal preferences [18], another, despite incorporating authority respondents, lacks a clear mapping of relevant competences and levels [10]. Lastly, the literature emphasizes the decommissioning SC, neglecting the broader responsibility of the OWE SC. Winkler et al. [15] stressed the importance of including manufacturers to evaluate their attitudes towards various EoL challenges.

Despite the inclusion of stakeholders in research on the EoL phase of OWE being in uncharted waters today, Spielmann et al. [10] underscored the need to identify relevant stakeholders early on to develop appropriate involvement strategies. Within offshore wind research, stakeholder engagement has been predominantly recognized in the realms of public acceptance [19–21] and marine spatial planning [22,23].

This study has a dual objective. Firstly, to comprehensively involve stakeholders in researching the EoL phase of offshore wind, integrating stakeholders from industry, government, research, and civil society [24,25]. Secondly, to assess stakeholder perspectives on EoL challenges across various phases and dimensions, aiming for a holistic understanding of major concerns. This approach enables the evaluation of stakeholder alignment or divergence in comparison to existing literature [17], bridging potential knowledge gaps. To evaluate stakeholder prospects and perspectives, the study employs semi-structured interviews, assessed through content analysis [26] and framework analysis [27,28]. Examining the Belgian case for offshore wind provides a diverse, easily accessible stakeholder environment coupled with essential scientific context, facilitating the interpretation of results. In this research, the following novelties are introduced: 1) comprehensive stakeholder mapping for EoL offshore wind, 2) incorporation of stakeholder perspectives in identifying and evaluating EoL challenges, and 3) a validatory qualitative analysis of expert insights, distinguishing between inside and outside experts.

2. Belgium's offshore wind landscape in a global context

Belgium stands as the fourth-largest European producer of OWE with 2.3 GW installed capacity in the Belgian part of the North Sea (BPNS) [29,30]. The country currently hosts eight operational OWFs [31,32], that generated an average annual output of 7,9 TWh in 2023, meeting 10 % of the national electricity consumption [30]. The Belgian OWE sector is concentrated, with four players owning and operating all eight OWFs, and two of these companies controlling six [31].

Belgian's offshore wind sector is poised for expansion under a new marine spatial plan targeting a total installed capacity of 3.1 to 3.5 GW [33]. The initiative includes developing the Prinses Elisabeth zone, divided into three plots, with tender documents for the first plot expected by the end of 2024 and operational turbines anticipated by late 2028 [34]. As the first offshore turbines approach the end of their estimated operational life, Belgium's domain concession spans for 20 years with a potential extension to 30 years [11]. Decommissioning of existing OWFs is scheduled between 2034 and 2047.

Belgium's role in the European offshore wind sector highlights its relevance, as it shares several similarities with other countries.

Firstly, the North Sea accounts for 80 % of Europe's total installed capacity, highlighting its significance [35]. Secondly, Diaz and Guedes Soares [36] noted that OWFs in Europe typically have water depths of 1 to 40 m, while in the BPNS, depths range from 14 to 40 m [31], representing a substantial portion of the European offshore wind infrastructure. Thirdly, in the BPNS, 86 % of the 399 wind turbines use monopile foundations, 12 % jacket foundations, and 2 % gravity foundations [31], aligning with broader European trends [35].

Belgium, lacking its own turbine manufacturers, primarily utilizes Danish Vestas and German Siemens Gamesa turbines [36]. The global nature of OWF installation involves major marine contractors from Belgium and the Netherlands [37], such as DEME, Jan De Nul, Van Oord, and Boskalis. This international collaboration fosters knowledge exchange, enhancing understanding of offshore wind dynamics and solutions to common challenges [37].

Examining the EoL phase for offshore wind assets in the BPNS may yield insights into challenges and solutions that could allow for contingent generalization to similar cases, consistent with George & Bennett's approach [38]. However, caution is necessary due to institutional and cultural differences among countries.

3. Materials and methods

The evaluation of anticipated EoL challenges comprised two phases. In Phase 1, a comprehensive literature review identified challenges [17]. In Phase 2, a stakeholder framework was constructed, participants were identified, and an interview guide was formulated. Two rounds of semi-structured interviews were conducted, recorded, transcribed, and analyzed for challenges using the coding framework from Phase 1. A schematic overview of this methodology is presented in Fig. 1.

3.1. Stakeholder framework and selection

The stakeholder framework based on the Quadruple Helix (QH) Model emphasizes key stakeholder engagement in fostering innovation [24,25]. It expands the Triple Helix model of industry, government, and research by adding civil society as a fourth category [39]. This adaptable framework accommodates innovations ranging from minor product advancements to significant societal transformations. In this study, the industry category was divided into the EoL SC, the OWE SC, and users of the sea.

For stakeholder selection, a detailed breakdown was necessary for industry and government to ensure diverse roles and perspectives related to the EoL phase were represented, preventing oversight of key actors. While diverse research perspectives could warrant detailed mapping, priority was given to those already engaged in

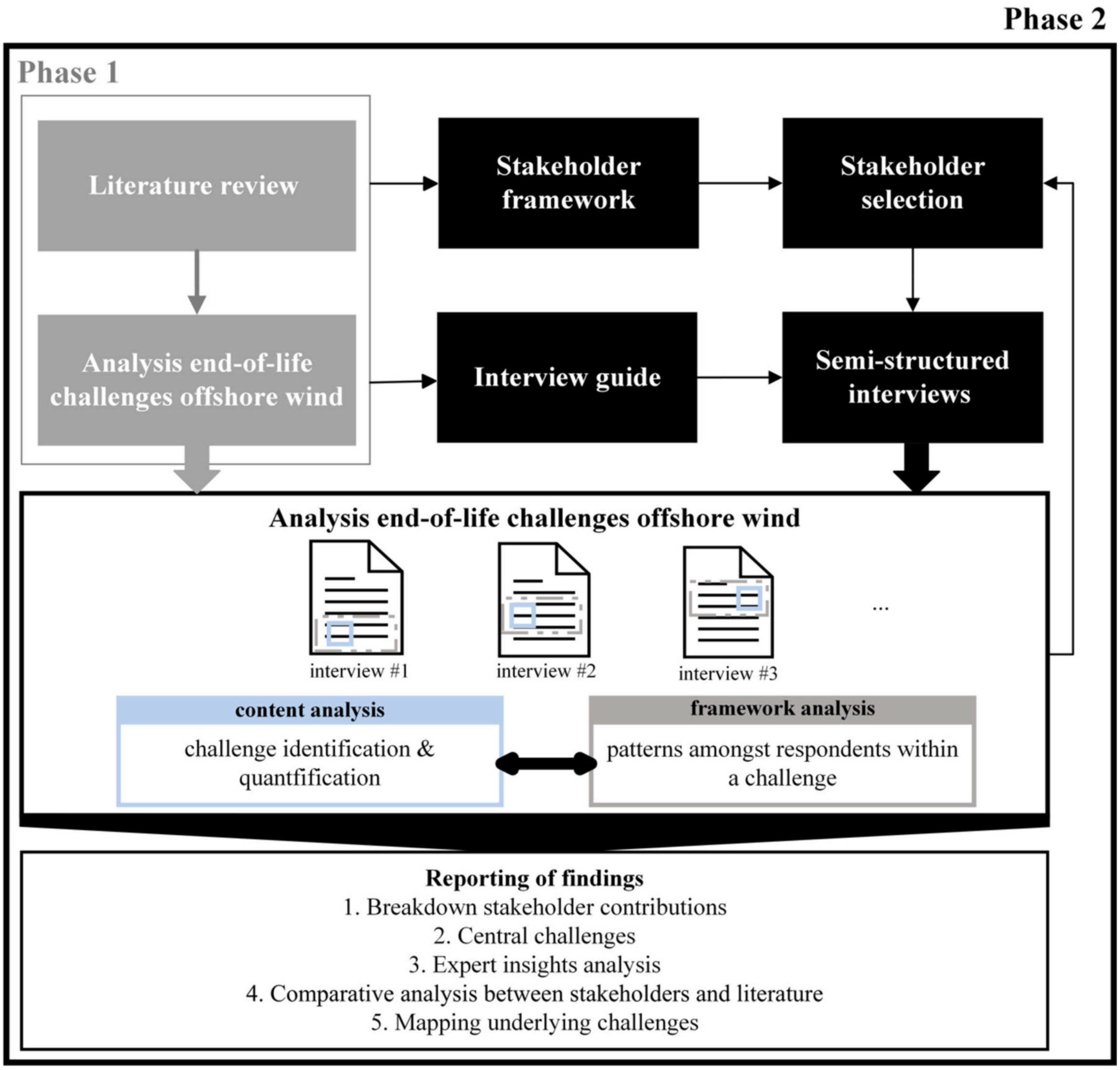


Fig. 1. A schematic representation of the methodological approach.

decommissioning projects or discussions, highlighting the most active researchers. More conclusive views from research covering more disciplines were incorporated through a comprehensive literature review conducted in Phase 1.

Civil society stakeholder selection was relatively straightforward, focusing on groups with broad societal and environmental concerns,

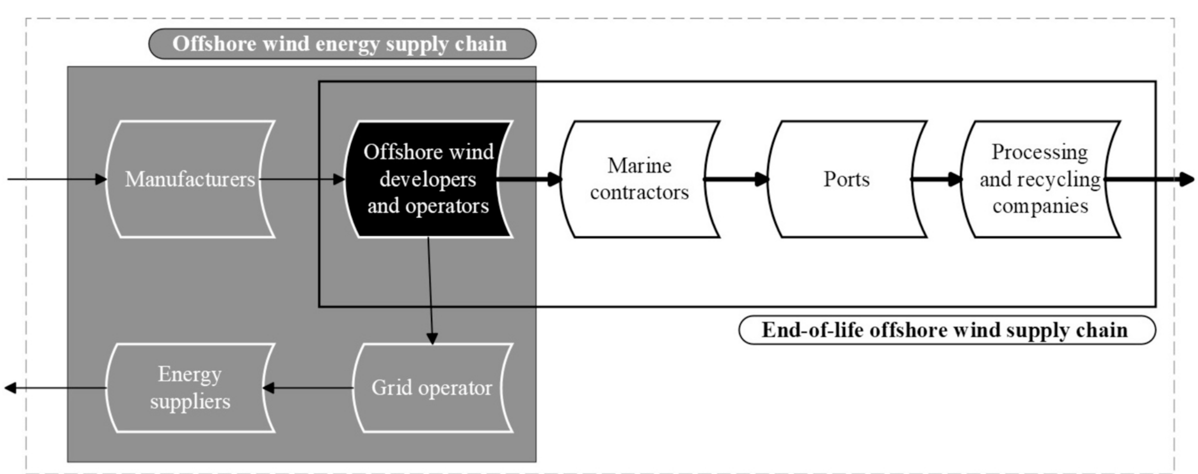


Fig. 2. Scheme for industry selection: two offshore wind supply chains.

prioritizing those engaged in ongoing discussions. Given the recent surge in organized stakeholder discussions [40] and the characteristics of the BPNS (Section 2), predominantly stakeholders engaged in Belgium were selected.

3.1.1. Industry stakeholder selection

To identify industry stakeholders, two SCs were outlined (Fig. 2). The EoL SC detailed the range from OWF operators to processing and recycling companies, validated against Winkler et al. [15]. The OWE SC was mapped out in a simplified manner allowing for the identification of key manufacturers of OWF components with knowledge regarding product design and processing potential. The electricity distribution chain was expanded from developers or operators to the grid operator and energy suppliers [41]. Stakeholder groups were refined in the first interview round, incorporating overarching trade associations.

3.1.2. Government stakeholder selection

From a governmental standpoint, the EoL phase involves diverse expertise, as highlighted by Spielmann et al. [10], encompassing authorities responsible for OWF approval, nature conservation, and economics. In Belgium, legislative power is divided between the central government and regional units [42]. While competencies are typically exclusive, some are shared when specific aspects of a competence are assigned to both the central and regional governments [43]. Fig. 3 illustrates the division of government competencies relevant to offshore wind decommissioning, spanning regional to international levels. Local governments hold significant competencies in public works and law enforcement [44], allowing them to support decommissioning primarily through coordination and execution, but are excluded from Fig. 3 due to their widespread presence.

3.1.3. Participants

A combination of purposive and convenience sampling was employed. Purposive sampling targeted individuals with specific knowledge and experience related to the EoL phase of offshore wind, ensuring diverse perspectives. Convenience sampling recruited participants readily available and involved in decommissioning discussions. Participants were asked to suggest additional stakeholder groups through snowball sampling [50].

Out of 32 contacted participants, 26 agreed to be interviewed

Table 1
Participants sorted by Quadruple Helix category and stakeholder group (total = 26).

QH category	Stakeholder group	No.
Industry – EoL offshore wind supply chain (6)	OWF operators and developers	3
	Marine contractors	1
	Ports	1
	Processing and recycling companies	1
Industry – Offshore wind energy supply chain (5)	Grid operator	1
	Energy suppliers	1
	Manufacturer offshore high voltage substations (OHVS)	1
	Manufacturer wind turbines	1
	Trade associations	1
Industry – Users of the sea (1)	Fishery	1
Government (6)	Local governments	1
	Waste authorities	1
	Energy authorities	1
	Marine environment authorities	1
	Maritime transport authorities	1
	European government	1
Research (4)	Scientific institution marine env.	1
	Scientific institution circularity	1
	Researchers (legal)	1
	Researcher (circularity)	1
Civil society (4)	Environmental NGOs	2
	Trade unions	1
	Citizen cooperatives	1

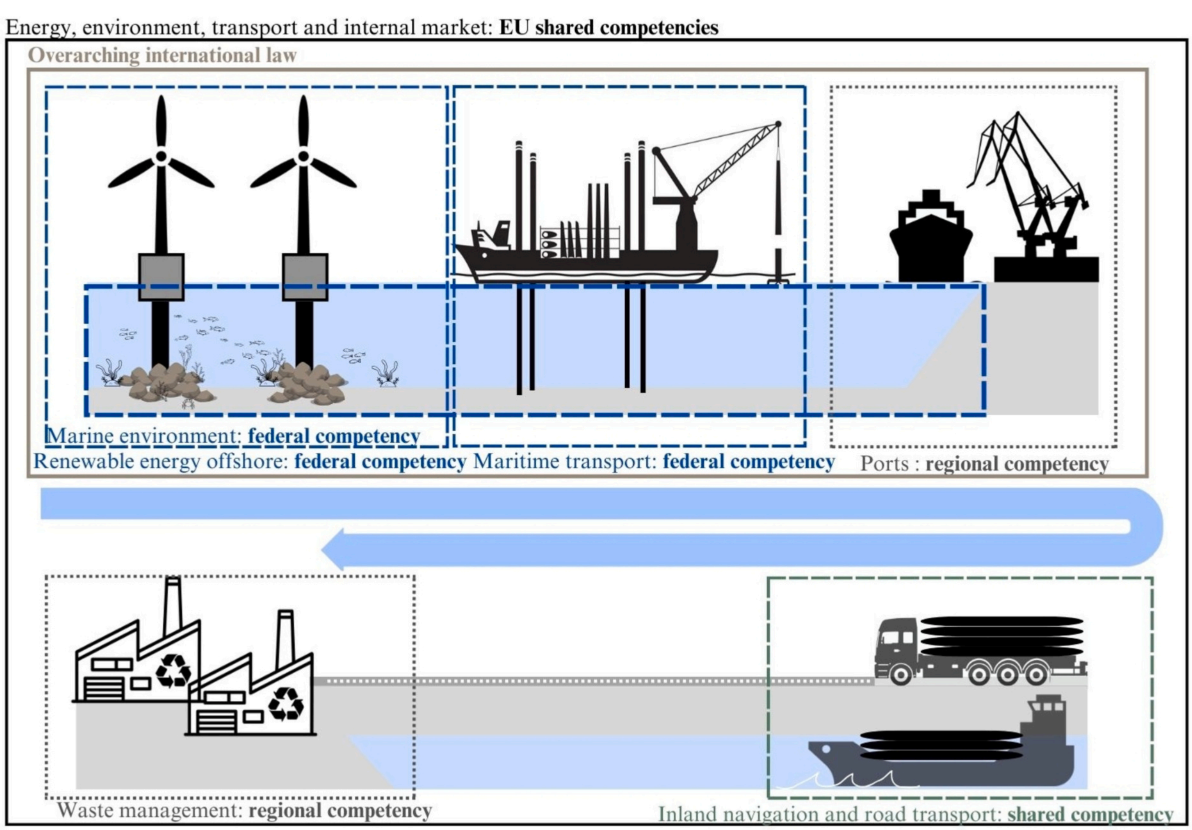


Fig. 3. Simplified division of government competencies for end-of-life offshore wind in the context of the Belgian Part of the North Sea [45–49].

(Table 1). Prior engagement and efficient scheduling contributed to the high response rate. Participants were categorized for anonymization and clarity without implying broad generalization. Although group sizes were limited, the study captures a wide range of perspectives, offering substantial breadth across the EoL phase. In rare instances, participants were chosen for their ability to represent their group's collective perspective, with the fisheries representative acting as a spokesperson for the local sector. In most cases, participants represented their organizations' viewpoints in stakeholder meetings. However, in the Belgian context, an organization may sometimes be considered a full group.

Port authorities, inland navigation authorities, and road transport authorities were excluded due to their minimal involvement in discussions. The industry is assumed to have the technical expertise to address port challenges. Knowledge of road transport and inland navigation is dispersed among stakeholders, making these authorities less relevant. Notably, no interviewed stakeholders suggested their inclusion during the snowball sampling process.

3.2. Interviews

Semi-structured interviews were designed [51] and conducted from January – March 2023 via Microsoft Teams. Participants answered open-ended questions structured around the five EoL phases, along with overarching inquiries. A comprehensive list of questions is available in Supplementary materials A. The average interview duration was 51 min, with the transcribed data totaling nearly 190 thousand words.

3.3. Analysis

The qualitative analysis of the transcribed data combined content analysis and framework analysis, as illustrated schematically in Fig. 1. In this study, content analysis, typically used to identify and quantify specific words, themes, or concepts to examine their presence, meanings, and relationships [26], was applied to identify challenges and count their frequency across different interviews. To provide the necessary depth, framework analysis was employed to organize the identified challenges around key themes, synthesizing the data [27,28]. This approach enabled the depiction and interpretation of patterns, facilitating an evaluation of the social meaning of each challenge.

This analysis began with the challenge coding framework developed in Phase 1 [17] which categorizes challenges across the five EoL phases and the five dimensions, yielding 25 potential sub-categories. This coding framework was applied to the interview data [28] using QSR Nvivo R 1.7.1 and underwent iterative refinement, initially guided by challenges identified in literature [17]. Fig. 4 illustrates the coding framework, focusing on economic challenges during the planning phase for illustration.

During the challenge identification process using content analysis, a more interpretive approach was employed to classify challenges based on stakeholder acknowledgement, laying the foundation for subsequent framework analysis. This flexible approach not only facilitated the identification of recurring issues and patterns within categories and interview segments but also explored the underlying reasoning and context to capture the richness of the qualitative data. Challenges were classified into two categories:

- **Acknowledged challenges:** Phenomena participants explicitly recognized as challenges (Supplementary materials B) or referenced indirectly, highlighting their significance through subtle expressions.
Acknowledged challenges: Phenomena participants explicitly recognized as challenges (Supplementary materials B) or referenced indirectly, highlighting their significance through subtle expressions.
- **Dismissed challenges:** Instances where participants rejected certain phenomena as challenges, indicating they viewed these issues as insignificant or irrelevant.

As illustrated in Fig. 1, the findings are reported from several angles, beginning with a stakeholder viewpoint to analyze participant inputs, followed by identification and interpretation of central challenges. Expert insights were analyzed (Section 3.4), and stakeholder results were compared with the literature, revealing novel challenges. A cross-case analysis mapped potential underlying challenges for central issues, exploring similarities and differences to support theoretical predictions [52]. The process utilized matrix queries in QSR Nvivo R 1.7.1.

3.4. Expert insights analysis

To address varying expertise levels among stakeholders, an additional analysis examined inside and outside experts' perspectives on EoL challenges. Inside experts, directly engaged in EoL projects, contrasted

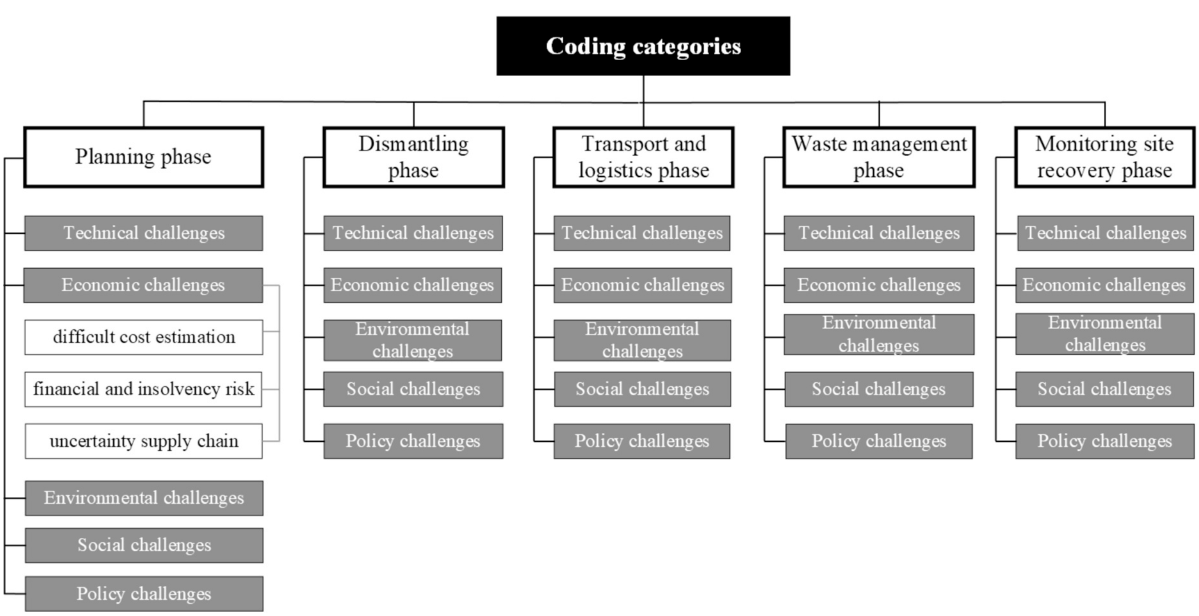


Fig. 4. Framework and segment coding categories: Illustration of economic challenges during the planning phase. While detailed breakdowns for each grey cell in the figure are available in the coding framework, they are not presented for readability purposes.

with outside experts from government and research, who provide valuable knowledge indirectly. Analyzing these insights separately enhances understanding. Expert participants were assigned to relevant EoL phases indicating their stakeholder group affiliation without necessarily representing the group's collective voice. Fig. 5 provides a visual overview of the respondents that were categorized as inside or outside experts across the phases, ensuring clarity regarding the methodological steps taken and the rationale for interpreting expert perspectives.

4. Results and discussion

4.1. Breakdown stakeholder contributions

All interviews consistently mentioned challenges. Among stakeholder groups, research participants acknowledged the most challenges, averaging 14 per participant, followed by those from EoL SC, government, and OWE SC. In contrast, civil society participants and users of the sea recognized fewer challenges, likely because the EoL phase has not yet begun in Belgium, projected to start in 2034 [49]. Consequently, public discourse is still developing, as it remains a lower priority for stakeholders not yet directly involved. Four out of five participants in these categories emphasized the novelty of the topic for them, with an environmental NGO actively engaged in marine issues as an exception.

At the participant level, the highest number of challenges were acknowledged by an OWF operator (19), closely followed by the trade association (17), the circularity researcher (17), an environmental NGO (17), and the energy authority (16). This pattern shows that nearly every QH category includes at least one participant who actively discussed EoL challenges.

4.2. Central challenges

In total, 67 challenges were identified, with most concentrated in the planning and waste management phases, focusing on technical and policy dimensions. A complete overview of the challenge mapping is available in the Supplementary materials C.

Central challenges were identified based on participant acknowledgement, leading to a deeper analysis of five pressing challenges. All QH categories addressed these challenges, except for users of the sea (Section 4.1).

4.2.1. Challenging recycling composites

The majority of participants acknowledged the technical challenge of **recycling composite materials** during the waste management phase, identifying it as a prominent concern in the interviews. The cross-linked nature of glass or carbon fiber-reinforced polymers used in wind turbine blades has been cited in the literature as a barrier to effective recycling [5,53]. This issue was echoed by participants from the EoL SC, who described blade recycling as complex and expressed doubts about recyclability. The processing and recycling company stated, "*Blades are cut into pieces and still end up in landfill along with residual waste. That is certainly not the right application. But well, we don't have a solution.*" An OWF operator noted that this issue extends to nacelle enclosures. The research category reiterated the challenges posed by complex material compositions, while civil society participants suggested repurposing blades for uses such as noise barriers.

Focusing on practical recycling solutions, the wind turbine manufacturer and the trade association emphasized innovations in epoxy-based blade recycling through resin system dissolution. However, the manufacturer explained, "*Right now, we are in a 2-year pilot phase where we will build two facilities: one to separate the blade materials, the second to recycle epoxy fragments.*" With projects still in pilot status, government participants discussed the lack of economically viable recycling techniques for blades. The waste authorities noted, "*There are techniques and technologies, but none that can yet be applied on a large scale.*" They and the energy authorities proposed incineration or cement co-processing as alternatives due to Belgium's landfill restrictions. The EU government representative referenced ongoing discussions about a potential EU-wide landfill ban for blades to incentivize industry.

In contrast, the circularity researcher viewed the issue with less concern, stating, "*I don't take such a big issue in the cement kiln coprocessing, I think we have to be pragmatic at this stage and design better blades for the future that can actually be recycled.*" Nonetheless, this perspective underscores the urgency for action to prevent worsening the existing problem.

For several stakeholders, the motivation to address this issue is clear: once an OWF begins decommissioning, the blades will be brought ashore, presenting a tangible challenge. The EoL SC, researchers, and waste authorities will directly be confronted with this issue, while stakeholders from the OWE SC and energy authorities may not feel the same urgency. Neglecting this visible problem risks the green reputation

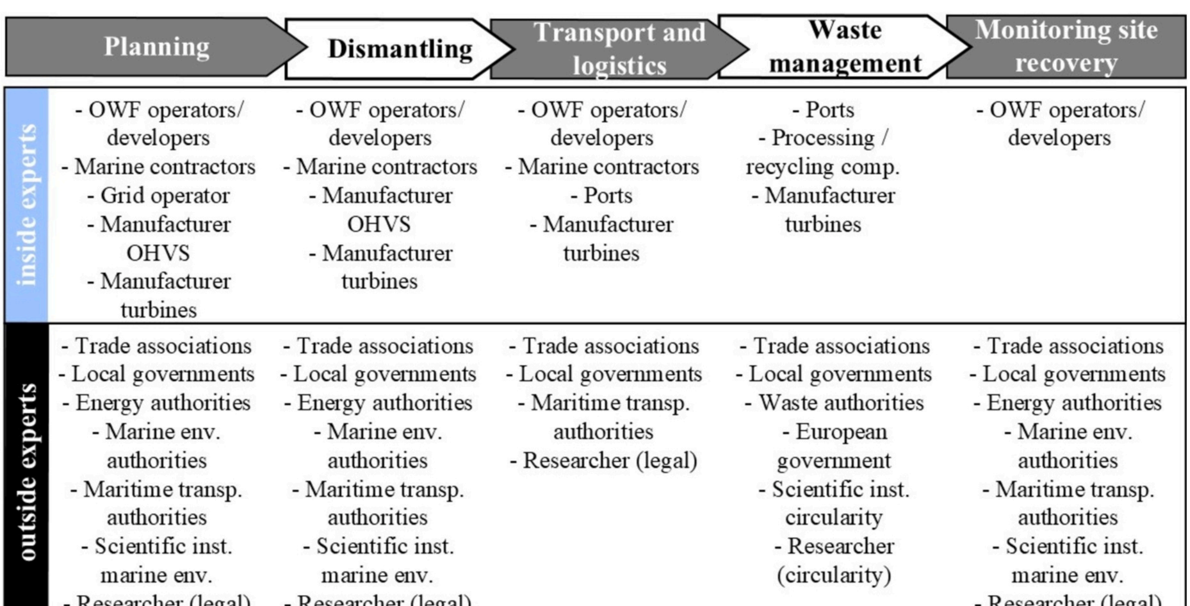


Fig. 5. Expert insights analysis – Categorization of stakeholder groups into inside and outside experts across the five end-of-life phases.

of wind energy, jeopardizing broader stakeholder ambitions. This highlights the need for proactive strategies to effectively manage EoL challenges and address public opinion concerns [17].

4.2.2. Inadequate removal legislation

A key policy challenge is the **inadequate removal legislation** in the planning phase. The ambiguity between partial and full removal of OWF components, combined with the lack of a standardized approach in Europe, has been highlighted in the literature as a significant hurdle for timely preparation and planning [15,49,54]. Specific aspects, such as the removal of submarine components like the scour protection, which must be fully removed under current Belgian regulations, and monopile foundations, which are required to be cut two meters below the seabed [49], were emphasized in the interviews.

Participants stressed the need for clear, flexible, and environmentally conscious decommissioning policies. EoL SC participants raised concerns about regulatory clarity, particularly regarding scour protection removal, highlighting the importance of clear legislation to address economic considerations and early planning challenges. OWE SC participants noted the urgent need to resolve the question of submarine component removal. A wind turbine manufacturer stated, "*I think it needs to be resolved by academics and policymakers because, if you ask the wind industry, they are obviously going to say, leave it. It's cheaper, right?*" The trade association also emphasized the importance of guidance from policymakers to ensure consistency across Europe and avoid repeating mistakes.

Researchers recommended flexible policies aligning with evolving technologies and environmental concerns. The marine environmental scientific institution noted, "*We know that in 20, 25, or 30 years, there will be much more knowledge and technology. So, I don't think it needs to be set in stone yet what will happen in 30 years*." They also suggested leaving certain components, like scour protection, in place to support environmental objectives, such as restoring gravel beds. Government participants acknowledged gaps in current legislation and discussed challenges in determining removal requirements. Waste authorities pointed out that the ambiguity in removal laws complicates onshore preparations, noting, "*They left room to revise the legislation by including a provision in the permits stating 'unless the minister decides otherwise.' However, we still don't know what the minister will decide*."

Interestingly, civil society participants did not raise the issue of inadequate removal legislation. An environmental NGO emphasized that full removal may be necessary due to the long-term technical and safety risks of partial removal.

The differing perspectives on OWF removal legislation reveal social and economic tensions. Industry participants prioritize regulatory clarity for effective planning, while marine environmentalists express contradictory views. Leaving certain components may support marine life but conflicts with their legal classification as waste, creating tension between environmental goals and regulations. These decisions also impact future offshore projects; partial removal may reduce immediate costs, but complicate or increase expenses for future developments.

4.2.3. Few ports suitable

A recurring technical challenge arises in transport and logistics, emphasizing **suitability of only a few ports** for decommissioning activities. To date, this issue has only been addressed by Jadali et al. [55], who highlighted that the limited number of suitable ports for decommissioning is influenced by factors such as distance, handling, and storage requirements. Yet, it was very notable in interviews with the EoL SC, research, and government.

Overall, participants most frequently mentioned the Belgian ports of Bruges and Ostend, as well as the Dutch Vlissingen as potential decommission ports. According to the EoL SC, the challenge revolves around restricted port space in the Belgian context, particularly in Ostend, currently the most active in offshore wind. The OHVS manufacturer expressed concerns about insufficient space in Ostend, citing logistical and accommodation challenges. However, the marine contractor stressed that other Belgian ports are generally unattractive for decommissioning due to distance or differing priorities. Participants from waste and marine transport authorities, as well as local governments, weighed the advantages of Ostend against alternatives like Vlissingen, outlining criteria for suitable decommissioning ports. The scientific institution for circularity and the legal researcher highlighted the importance of large ports, nearby waste facilities, and circular economy principles, while an environmental NGO prioritized easy transportation and adequate storage.

The issue of limited port suitability is closely tied to the broader policy challenge of missing decisions on port expansions. Recognizing space constraints, the participating port seeks to convince policymakers that expansion would yield valuable returns while leveraging local expertise and businesses. The port stated, "*If they want these Belgian wind farms to be built from a Belgian port and within a Belgian context, please provide us with the necessary resources*".

Perspectives on port suitability underscore the tension between technical feasibility and national interests in developing a Belgian EoL SC. Policymakers face a crucial choice: maintain the status quo, potentially losing business by shipping waste to better-equipped ports abroad, or pursue government intervention to strengthen Belgium's renewable energy sector.

4.2.4. (Artificial) reef effects

Many participants from OWE SC, research, and civil society raised the environmental challenge of **(artificial) reef effects** at dismantling. Literature often highlights the ecological benefits of OWF components as artificial reefs, suggesting that partial removal can balance environmental preservation with decommissioning needs [17]. Participants voiced concerns about the substantial increase in marine life around offshore wind structures. Considerations include uncertainties about complying with removal regulations for submarine pieces involving ecological impact, legal aspects, and the dilemma between ecosystem restoration and reverting to the compromised pre-installation state impacted by prior human activities. The debate revolves around whether to restore the environment by removing structures or preserve the altered habitat.

The OWE SC showed support for maintaining structures for ecological benefits. The trade association noted, "*Even if you're restoring to the original condition, what if the original condition is worse than the condition it is now? Then maybe we shouldn't restore to the original condition*." Civil society participants expressed biodiversity concerns, with the citizen cooperative stating, "*We always think, isn't it good that different wildlife is appearing around those wind turbines*." Meanwhile, an environmental NGO called for the thoughtful redistribution of protected marine zones.

Research highlighted the complexity of decommissioning, especially regarding foundations. The legal researcher reiterated analogies made by NGOs in the context of rigs-to-reefs, stating, "*If you park an old car in the woods because you want to get rid of it, sure, moss will grow on it and maybe squirrels will move in, but in the end, you're still parking an old car in the woods*." Government participants discussed the fate of seabed structures, with marine authorities stating, "*These are difficult questions. Ultimately, a minister will have to decide on this, right?*"

This challenge mirrors a broader ecological dilemma. Some advocate intervention to restore biodiversity, while others value the modified ecosystem. The OWE SC's acknowledgment of this issue raises questions about underlying incentives. The discussions reflect societal values about the marine environment but also warrant scrutiny for potential perception management, as seen in the rigs-to-reefs debate [56].

4.2.5. Unclarity surrounding the most efficient dismantling approach

While not covered in Phase 1, several participants emphasized the economic **unclarity surrounding the most efficient dismantling approach**. The discussion on which components to remove at EoL offered no clear guidance on the methods. Stakeholders were unable to provide a definitive answer to this challenge.

OWF operators and the processing and recycling company debated the merits of "reverse installation" and cutting structures offshore for easier transport, weighing cautious disassembly against cost-effective methods. One operator noted, "*Questions arise, such as whether we should partially dismantle components offshore to make them easier to transport? I don't know*." The marine contractor, however, did not view this as a concern, possibly because inefficiencies during dismantling primarily affect owners financially, with time delays increasing costs under day-rate contracts.

OWE SC participants also raised logistical challenges, considering options such as shredding components for transport efficiency. Offshore downsizing was a recurring theme, with government participants exploring the use of recycling pontoons at sea. A circularity researcher noted, "*I think you would ideally already do the assessment and the downsizing at sea, because then you can fit more onto a ship and probably also use smaller ships*." The trade union, focused on financial considerations, expressed interest in on-site material processing, particularly for blades. However, the marine environmental scientific institution cautioned, "*That certainly has environmental risks*."

Offshore downsizing introduces SC uncertainties at EoL [15], emphasizing the need for assessments to compare dismantling methods. Promoting efficient approaches could benefit offshore renewables and society by reducing the costs of decommissioning and their impact on electricity prices.

4.3. Expert insights analysis

4.3.1. Expert acknowledged challenges

Expert participants widely recognized the central challenges (Section 4.2), while both internal and external experts introduced additional challenges.

Inside experts highlighted a planning challenge: the **loss of technical information** during an OWF's lifetime due to contracting norms and intellectual property considerations. While Winkler et al. [15] linked contractual schemes to broader SC uncertainties, our interviews specifically noted concerns about technical information losses. For wind turbines, an OWF operator highlighted complexities of information sharing and stressed the need for strategic planning and possible policy interventions. Examining the root cause, the operator remarked, "*There are actually only two major players offshore right now, maybe a third, and later the Chinese. But yes, that's almost a monopoly situation*." The wind turbine manufacturer acknowledged this concern, "*Manufacturers are not very excited to hand over blueprints*", but mentioned initiatives like material passports to balance sharing and intellectual property protection. For OHVS, the challenge was reversed, with manufacturers lacking access to operational data for lifetime extension.

This challenge reflects tension between competitive interests and the collaboration needed for sustainability and innovation. Stakeholders show a willingness to cooperate, recognizing the importance of shared knowledge and alliances.

Nearly all outside experts acknowledged the challenge of **cost and availability of vessels**. This challenge is widely noted in the literature, emphasizing competition for resources among offshore wind, oil and gas, and civil construction sectors [57]. The trade association stated, "*There will be a vessel shortage for installing turbines by 2030. But if we are stretched for vessels to install turbines, we will also have no vessels available to decommission the existing ones. So, how do we deal with that?*" They proposed incentivizing marine contractors to continue operating their older smaller installation vessels to optimizing resources. The local government raised risks associated with vessels deployed outside Belgium, suggesting alternative dismantling approaches, while the legal researcher anticipated increased costs due to competition for specialized vessels. Inside experts confirmed this challenge, but the marine contractor pointed towards the cyclical nature of vessel availability, noting, "*Currently, there is limited capacity available, but that will change. It is now 2023, but who says it will still be like this in 2027 or 2028?*" They recommended flexibility in decommissioning to reduce costs and improve timelines through strategic planning and collaboration with clients.

Potential vessel shortages underscore the need for strategic planning and collaboration to allocate resources effectively and meet project timelines. Most parties are committed to finding practical solutions, emphasizing collective action to navigate challenges and optimize resource use.

4.3.2. Expert dismissed challenges

Some challenges were explicitly dismissed by experts, with key debates focusing on waste management.

In the literature, concerns were raised about **limited refurbishing and reuse potential** due to factors like age, assembly, and corrosion [58]. However, this challenge was dismissed by the port, trade association, European government representative, and circularity researcher, with none of the other experts acknowledging it. The port referred to industry plans, "*Part is not intended to be decommissioned and scrapped, but decommissioned and simply reassembled elsewhere*." The others confirmed a vibrant secondhand market for onshore turbine reuse and indicated potential for reusing nacelles or blades from OWFs. While the wind turbine manufacturer acknowledged the active secondhand turbine market for onshore turbines, they could not confirm if a similar market would develop for offshore turbines. The circularity researcher noted resistance, stating, "*In the UK, I would say that there is a resistance towards the idea of reusing parts from offshore wind.*"

The discussion reveals that despite the uncertainties, reuse should not be dismissed, but preferred. Although intentions for reuse are present, evidence of a market is lacking, which is not surprising at this early development stage. Since offshore component fatigue varies due to multiple factors [59], the potential for reuse will likely differ across and within OWFs. Consequently, experts' optimistic views on developing a reuse market will depend on tailored assessment methods [17].

A potential technical challenge was raised by the circularity researcher, being **ungrounded recyclability claims**. They observed, "*The wind industry is communicating that 85 to 90% of a turbine can be recycled. I looked into the basis of those claims and was traced back to one particular article, that's already quite old and had no empirical grounding in it to support that.*" According to the researcher, complexities such as coatings on steel components can complicate recycling processes and potentially reduce the amount of recyclable material. This issue was not mentioned by several experts discussing recycling rates, including an OWF operator, the port, and the wind turbine manufacturer. The trade association explained, "*85-90% of the mass is recyclable, because it is steel, copper, aluminum. Well-established practices for that, [...] it goes to a steel scrap yard, they know what to do with it, no worries*." Similar views were shared by participants from European government and the scientific institution for circularity.

Among the experts, perspectives on recyclability claims differ. Industry participants emphasize high recyclability rates, while a researcher critically examined these claims, pointing out potential evidence gaps. Other experts appeared to accept the industry's statements without further examination. As public discourse grows, especially with more stakeholder meetings (e.g., [40,60]), evaluating and verifying these claims becomes essential, as discrepancies between claims and actual recyclability during decommissioning could challenge public perception (Section 4.2.1).

4.4. Comparative analysis between stakeholders and literature

Technical and policy challenges were significant in both the literature and interviews, but the interviews revealed new issues and downplayed economic concerns. Stakeholders also focused more on policy challenges during the waste management phase.

Central stakeholder challenges include four Phase 1 framework issues [17] and one novel challenge: **unclarity surrounding the most efficient dismantling approach**, suggesting that literature may not fully reflect public concerns.

The literature did not raise the challenge of **unclarity surrounding the most efficient dismantling approach**, but two related challenges were identified. First, **difficult cost estimation**, influenced by limited experience, changing regulations, supply chain issues, and uncertainties, received significant attention [17]. Second, Winkler et al. [15] highlighted **SC uncertainty** within the decommissioning process, driven by technological uncertainties and critical downsizing points. The interviews suggest these uncertainties contribute to financial concerns from not only the EoL SC but also the broader wind industry, government, and research sectors. This is likely linked to financial uncertainties and insolvency risks for OWF owners [17]. Developing methods to identify the most efficient dismantling approach could mitigate these risks. Thus, the findings support the need, as suggested by Winkler et al. [15], for quantitative assessments of different decommissioning scenarios, particularly regarding cost estimation.

Fig. 6 illustrates the emphasis on central challenges in both the literature review and stakeholder interviews in a treemap. The size of the boxes represents the relative frequency of each challenge being mentioned with larger boxes indicating challenges that were more frequently highlighted.

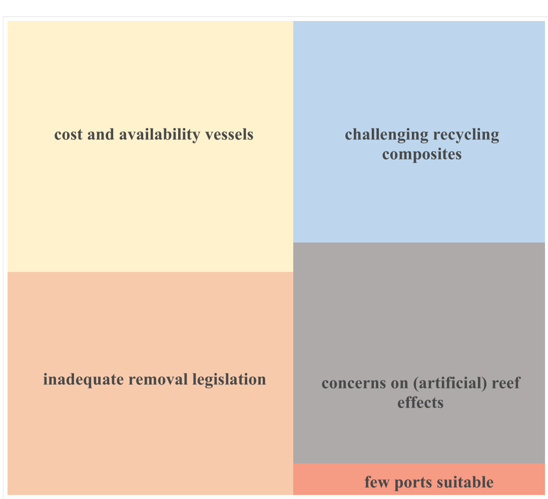
The figure reveals notable shifts in focus between the two sources. **Vessel cost and availability** emerge as a key challenge in the EoL literature [17], but received comparatively less attention from stakeholders, particularly those outside industry. This discrepancy highlights differing perspectives, with industry experts more concerned over operational logistics, due to financial impacts.

Stakeholder-literature gaps appear in the **port suitability** challenge [55], with half of the interviewees raising it. The interviews indicate this issue is particularly pressing in Belgium, where space constraints likely intensify the problem. However, the high utilization density of seaports in nearby regions [61] suggests that port suitability challenges may extend beyond Belgium. In the EoL literature, only Jadali et al. [55] noted the limited number of ports equipped for decommissioning due to the specific handling and storage requirements. This discrepancy underscores the need for a thorough assessment of offshore wind decommissioning and repowering port requirements, along with systematic mapping of North Sea ports. While installation has such initiatives [62], decommissioning evaluations remain confined to grey literature [63].

The interviews revealed 27 novel challenges, emphasizing potential issues overlooked in existing studies. This omission may stem from knowledge or perceptions gaps. Acknowledging a time gap between academic literature and stakeholder discussions, this is partially addressed by incorporating publications nine months post-interviews. While some challenges may be covered in upcoming publications, comprehensive coverage seems unlikely. Since a substantial portion of participants emphasized these challenges, they should be considered in decision-making and future research.

In the planning phase, participants raised the challenge of **unclarity in grid connection and electricity production**. The OWF operators, port, energy supplier and OHVS manufacturer expressed concerns about production disruptions lasting 6 months to 3 years due to repowering unclarity. Citizen cooperatives stressed careful consideration of energy production reductions and a phased decommissioning approach. Despite these concerns, the Belgian grid operator was optimistic, stating, "*Those wind farms of 200 or 300 MW, the first ones that will go, those are manageable numbers. We can find solutions for those.*" This finding indicates some misinformation or speculation among stakeholders reliant on energy production. While discussions about the EoL phase have begun in Belgium [40], energy sector decision-makers seem less engaged, leaving many questions unresolved and amplifying concerns about production disruptions and energy security. This may have led participants to confuse the manageable decommissioning of smaller OWFs with the complexities of the nuclear phase-out [64], underscoring the necessity for greater transparency and increased involvement of energy decision-makers in public discourse.

In waste management, the **lack of waste legislation** poses legal uncertainties. The port and trade association noted issues with waste classifications and codes, emphasizing regional and international discrepancies. Concerns about blade material composition add to the confusion. The trade association noted, "*The different waste codes apply and the blades get lost basically in a stream of construction and demolition waste, which makes it very hard for recycling companies that are specializing in composite material recycling to actually find these blades and get them recycled.*" Additionally, the circularity researcher highlighted inefficiencies in enforcing the waste hierarchy in the UK. The OHVS manufacturer, energy authority, and trade union emphasized risks of unethical waste shipments and called for a clear legislative framework to avoid pitfalls. Notably, these issues were not raised by the processing and recycling company, waste authority, or the EU government representative, suggesting they may be unaware of these challenges or do not consider them urgent. Nevertheless, it would be beneficial for



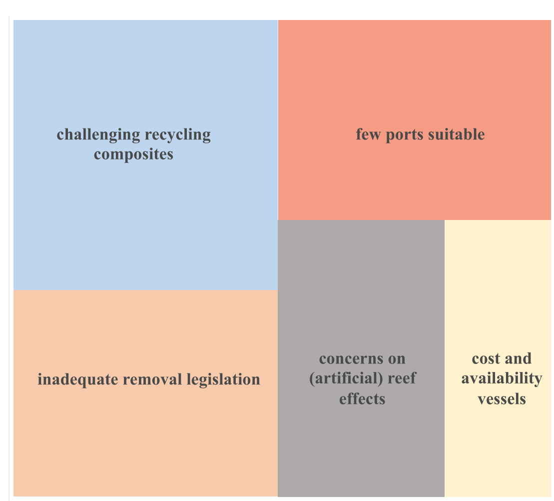


Fig. 6. Most acknowledged central challenges in both literature (A) and by interviewed stakeholders (B).
Source: authors analysis in combination with Vetters et al. [17].

responsible stakeholders to clarify these issues to prevent intensifying other waste management challenges through policy inefficiencies.

In monitoring site recovery, a novel policy challenge arose regarding **rest liabilities for components left in situ**. While previous research addressed ownership and responsibility during decommissioning [15], the question of responsibility post-project has received little attention. This issue is especially relevant when parts of an OWF, particularly the foundations, are left in place. Participants from local, energy, and waste authorities expressed concerns about often-overlooked residual liabilities, emphasizing the need to identify accountable parties and secure environmental permits. The energy authority explained, "*If the remaining part of the pile resurfaces, who is responsible if someone gets stuck on it? […] Either there is a new responsible party, or you remain the last one responsible and need to clean it up and remove it completely*." The marine environmental scientific institution deemed the issue as complex, as both industry and government show disinterest in this liability. The environmental NGO questioned the feasibility of deferring responsibility, stressing the imperative for current accountability. Notably, industry participants did not recognize this issue, believing their liability ends once they meet legally required removal standards. However, for other stakeholders, the question of responsibility is less clear-cut. Many overlook long-term monitoring costs and implications of delayed decommissioning, which could exceed savings from partial removal. This highlights a significant social dilemma where short-term economic gains overshadow long-term environmental responsibility, raising questions about the societal benefits of partial decommissioning.

4.5. Mapping underlying challenges

4.5.1. Challenging recycling composites

Stakeholder challenges reveal interconnection. Due to widespread concerns about composite recycling, Fig. 7 maps potential underlying challenges by illustrating other challenges raised by participants raising the central challenge.

Recycling composites is linked to **loss of technical information** and **lacking circular design**. The wind turbine manufacturer emphasized technical information problems, particularly for blades (Section 4.3.1). Five participants stressed lacking circular design in composite materials and blades. The waste authority and scientific institution for circularity expressed concerns about the industry's preference for cost-effective glass fiber in blade design, despite carbon fiber's recycling benefits. The connection to the technical challenge of **complex material composition** is evident. The processing and recycling company and research participants noted that material composition and location for blades are often unknown, hindering recycling efforts. The processing and recycling company remarked, "*With the mass balances theoretically, you don't get very far. You really need samples or sufficient material to conduct an industrial test.*"

Missing volumes today and the **absence of a business case for EoL blades** can hinder blade recycling. While the OWF developer, processing and recycling company, and wind turbine manufacturer acknowledged that limited volumes, especially for blades, hinder investments, local and waste authorities, along with the legal researcher and scientific institution for circularity, pointed out that recycling technologies are not yet prepared for scaling. The main challenge is that recycled materials, despite their environmental advantages, are currently less valuable and more expensive than virgin materials. In discussing glass fiber recycling, where virgin materials are particularly inexpensive, the scientific institution observed, "*You actually end up with an even lower-quality product that you want to bring to market, so it's also very difficult to sell that at a higher price than your initial value.*"

The policy landscape, encompassing **lacking government support**, **waste legislation**, **European cooperation**, and **encouragement towards circular practices**, likely amplifies the central challenge. While the connection with lacking waste legislation was explained earlier (Section 4.4), several participants emphasized the need for European cooperation through unified strategy, collaboration for material processing pilot projects, and coordination to manage material fluctuations during decommissioning. While the wind turbine manufacturer and the European government representative downplayed the need for additional encouragement towards circular practices, several participants emphasized its significance in tenders. The scientific institution for circularity identified lacking government support as a critical factor contributing to the failures of startups in blade recycling.

A two-fold approach is recommended for addressing the challenge of composite recycling, considering strategies for both new and older wind turbine blades.

First, to improve new blades entering the market, it is essential to resolve underlying technical challenges. Initiatives like material passports [65], recyclable blade designs [66], and non-price criteria in tenders [67] aim to tackle these issues. Evaluating the effectiveness of these measures is advised before considering additional incentives like Extended Producer Responsibility concepts, material substitution, or efficiency strategies [68]. These steps may kickstart a business case for future EoL blades, along with exploring the impact of different design scenarios on EoL economics.

Second, addressing challenges for existing blades is crucial, as, without implied bans [69], they can constitute 40 % of landfilled material, despite being less than 1 % of the total installed mass in an OWF [70]. Improving composite recycling involves resolving policy issues

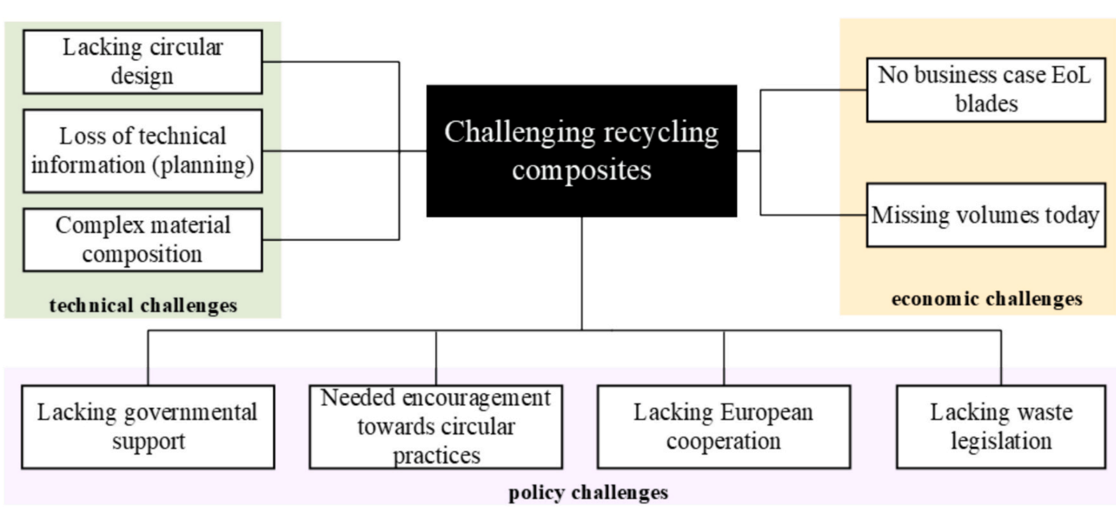


Fig. 7. Underlying challenges for challenging recycling composites.

within waste legislation. Industry collaboration, with government support, can facilitate research efforts, allowing a transition from pilot projects to scalable solutions. Additionally, assessing the economic viability of early recycling technologies is key to prioritizing and supporting those with the greatest market potential.

4.5.2. Inadequate removal legislation

Fig. 8 illustrates potential connections between the inadequate removal legislation and other stakeholder challenges. This issue extends to dismantling and monitoring site recovery phases, with challenges grouped by dimension for clarity.

Participants frequently linked environmental challenges with inadequate removal legislation. Notably, dismantling challenges, including **(artificial) reef effects** (Section 4.2.4) and **disruption effects**, were consistently raised. All participants from OWE SC and research addressing the central challenge also emphasized reef effects. Disruption effects, while less frequently mentioned, were exclusively highlighted by participants concerned with removal legislation. The marine environmental scientific institution stressed underwater noise disruption, while both the energy and marine environmental authorities, along with the legal researcher proposed suitable removal techniques to mitigate impacts instead of advocating for legislative adjustments.

Connected environmental challenges also arise in the planning phase, including **scarce knowledge on marine impacts** and **challenges in weighing** them. The marine authority and the marine environmental scientific institution emphasized uncertainty about the species impacted by OWF removal and the extent of impacts. Even with clear biodiversity data, monetizing and weighing impacts remains challenging. The participating marine environmental scientific institution stated, "*There are already tools for assessing ecosystem services and impacts, but it is, and always will be, very difficult to assign weight to certain factors*." The environmental complexity extends to monitoring site recovery through **potential risks associated with leaving components** in place for natural decomposition.

Technical uncertainties, particularly in monitoring site recovery, play a crucial role in removal discussions. This is highlighted by **technical hazards associated with leaving components in situ**, especially for repowering in the constrained space of the BPNS and long-term monitoring needs. Industry participants frequently raised technical challenges related to dismantling, with two challenges, **complex operations** and the **complex removal of scour protection**, exclusively discussed by those addressing the central issue. Participants acknowledged the **complex removal of foundations** irrespective of their stance on removal legislation, emphasizing a lack of overall experience. The difficulty level varies based on factors like foundation types, seabed and sediment conditions, and removal requirements, highlighting the underlying technical challenge of **differences between OWFs**. Despite challenges, the marine contractor and the OWF operators and developers expressed optimism about future removal options, with expectations that streamlined removal legislation will drive technological development and adoption across the North Sea.

Underlying policy challenges contributing to the central challenge were raised primarily by non-industry participants. The trade association and legal researcher raised concerns about the **oil and gas focus** of international removal legislation like UNCLOS (United Nations Convention on the Law of the Sea) and OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic), questioning its applicability to OWFs. The legal researcher explained, "*There is all sorts of legislation that is heavily based on oil and gas platforms. And, well, there are simply differences between oil and gas platforms and wind turbines*." Policy challenges, such as **monitoring in situ options** and **unclear rest liabilities** (Section 4.4), support the case for complete removal.

Social challenges were less emphasized, especially by industry. While safety during dismantling was not seen as challenging, concerns about **in situ safety hazards** arose in the context of reopening OWF sites for marine transport or seabed-disturbing activities. If components are left in situ, safety precautions would likely be implemented, minimizing the need to reconsider this dimension of removal legislation.

Underlying economic challenges were rarely discussed, with only the trade association mentioning **costly cable and foundation removal**. Most participants, including industry, prioritized environmental and technical concerns over economic factors. However, the intricate link between technical and economic aspects means that more complex operations tend to be more expensive, reflecting the wind industry's focus on environmental considerations over financial incentives.

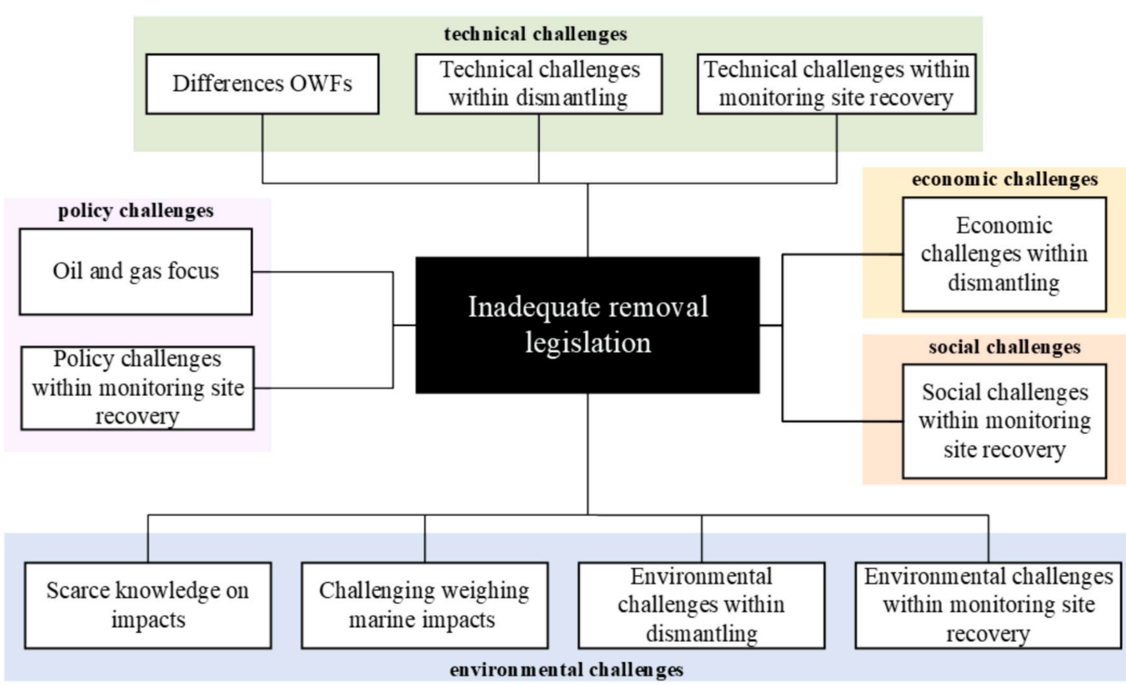


Fig. 8. Underlying challenges for inadequate removal legislation.

Customized strategies, aligning with unique political priorities, are recommended to address inadequate removal legislation, focusing on key areas such as energy supply, industry strengthening, and marine environment. These recommendations are applicable beyond the Belgian context.

For policy makers prioritizing energy supply, recommendations depend on the availability of offshore space for wind development. In countries with limited space, such as Belgium, incentivizing full removal is crucial to address monitoring site recovery challenges and enable site reuse for repowering. In less restricted countries, such as the UK or Denmark, partial removal could be explored without compromising overall energy production, leveraging flexibility in marine spatial planning [71]. However, initial sites may hold the highest technical and economic potential [72], a critical consideration in repowering discussions [73].

For industry strengthening, aligning with industry calls for streamlined removal legislation is essential. While tailored solutions are likely needed for marine environmental considerations, standardization can drive industry investment in removal technologies. Recognizing the importance of standards in rapidly adopting emerging technologies [74], a cross-border standardization approach could make advanced removal technologies economically viable for marine contractors, enhancing efficiency, safety, and cost-effectiveness across projects [75]. For standardization, international forums, including multilateral agreements in ongoing North Sea collaborations [76], are essential. International platforms like UNCLOS and OSPAR offer avenues to amend international removal legislation, focusing on offshore renewables and standardization.

If the marine environment is prioritized, the strategy depends on decommissioning urgency. Countries with ample time before decommissioning planning may await additional scientific research on removal impacts [17], aligning with Belgium's decommissioning timeline [49]. Conversely, countries like Denmark, the UK, Germany, and the Netherlands, facing more immediate decisions [77], may favor a second approach. The first removal decision should consider the project's context, including foundation types, underground conditions, and a country's energy supply or industry strengthening needs. To ensure environmental goals, initial projects should be knowledge-gathering opportunities, informing scheduled legislative revisions.

4.6. Enhancing the literature on stakeholder engagement and end-of-life challenges

This study has played a considerable role in advancing the understanding of stakeholder engagement and addressing gaps in the EoL literature. Incorporating diverse stakeholders is crucial for understanding EoL challenges in offshore wind. Existing literature often treats civil society stakeholders hypothetically, with limited empirical engagement [18]. This study includes perspectives from two environmental NGOs, a trade union, and a citizen cooperative. Although these participants identified fewer EoL challenges due to the topic's novelty, they raised important ethical issues, such as potential illegal waste shipments and industry practices of deflecting responsibility, underscoring the need for inclusive engagement.

The complex policy landscape is often oversimplified in the literature, with various involved government entities overlooked [10,18]. The legal and policy framework governing EoL in Belgium was analyzed in-depth (Fig. 3), followed by interviews with local governments, waste authorities, energy authorities, marine environment authorities, maritime transport authorities, and the European government representative. Engaging these representatives enriched the understanding of critical EoL challenges.

Existing research emphasized the EoL SC, neglecting the broader OWE SC responsibilities, despite Winkler et al. [15] highlighting the importance of including manufacturers. Our study expanded this focus, incorporating perspectives from grid operators, energy suppliers, and manufacturers (Fig. 2). Their insights revealed challenges such as loss of technical information and clarified issues related to grid connection and electricity production.

This study enhances the understanding of EoL challenges by highlighting gaps between existing literature and stakeholder perspectives. Fig. 6 shows divergences in emphasis on key challenges, particularly regarding port suitability and vessels. Stakeholders expressed uncertainty about efficient dismantling methods, discussing reverse installation and offshore downsizing. Concerns about potential disruptions in grid connection during repowering revealed misinformation among Belgian stakeholders. Additionally, legal uncertainties within the waste legislation complicate recycling efforts and raise issues of residual liabilities for components left in situ post-decommissioning. These aspects remain largely unaddressed in the literature, highlighting opportunities for policy development and further research.

4.7. Limitations

This study has some limitations. First, differences in stakeholder expertise were recognized, leading to the expert insights analysis. Second, stakeholder perspectives may rapidly evolve, making this study a snapshot in time.

Third, while the BPNS serves as a strong case (Section 2), some outcomes may vary in other contexts due to diverse regulatory landscapes and local infrastructures. These potential variations were noted in relevant challenges, particularly for port suitability, where systematic mapping of North Sea ports based on decommissioning requirements was advised. Furthermore, comparing findings with existing literature has served as an initial step in testing contingent generalizations, offering a preliminary assessment of their applicability to similar cases.

Fourth, acknowledging the lack of a fully representative sample is crucial, given the qualitative approach prioritizing understanding and interpretation [78]. Purposive and convenience sampling were combined to access diverse perspectives essential to the research objectives, considering the time-intensive nature of conducting and analyzing interviews.

Finally, while the interviews enabled stakeholders to highlight key topics, time constraints may have restricted a comprehensive coverage of their perspectives. The absence of a stakeholder view on a challenge does not indicate a lack of opinion, however, the goal was to unveil key perspectives on challenges rather than provide exhaustive coverage.

4.8. Policy implications

This study yields key policy recommendations for effective planning. Acknowledging novel challenges is recommended for decision-making and future research. Enhanced transparency in grid connections is necessary to combat misinformation related to grid challenges during decommissioning, especially with the increased political emphasis on energy security. Addressing inadequate removal legislation requires a multifaceted approach. In space-restricted countries prioritizing energy supply, incentivizing full removal strategies is vital. Strengthening industry involves aligning with calls for streamlined removal legislation and standardization. For those emphasizing marine environmental concerns, revisiting removal legislation with environment considerations is suggested, pending further research. Countries with immediate decommissioning needs should implement timely legislative revisions based on initial experiences.

In transport and logistics, the interplay between vessel cost and availability reveals how an economic challenge for one stakeholder can benefit another. Despite the predicted global increase in vessel numbers [79], continuous monitoring of supply and market dynamics is recommended. Additionally, addressing vessel availability concerns beyond EoL and offshore wind advocates for a broader sectoral approach. Lastly, assessing port requirements for both decommissioning and repowering is recommended, systematically mapping North Sea ports based on these criteria. This approach can foster stakeholder dialogue and address urgent suitability issues.

In waste management, resolving technical challenges in designing new blades is crucial. Before introducing additional incentives for circular practices, ongoing industry and policy initiatives should be thoroughly assessed. For existing blades, resolving complex composites recycling requires addressing policy issues, fostering collaboration among stakeholders, securing government support, expediting research, and prioritizing economically viable early recycling technologies.

5. Conclusions

This study qualitatively assessed the phases of the decommissioning EoL strategy for OWFs through semi-structured interviews along with framework and content analysis. Engaging 26 stakeholders from industry, government, research, and civil society, revealed 67 challenges surpassing the 46 identified in the literature.

Key challenges included composite recycling, removal legislation, port suitability, (artificial) reef effects, and unclarity surrounding the dismantling approach, highlighting the complex interplay of ecological, regulatory, and economic factors that influence public perceptions and stakeholder engagement in OWF decommissioning.

In a validating expert insights analysis, participants confirmed key challenges, identified additional ones, and dismissed some waste management issues. This underscores the need for greater collaboration and transparency to promote sustainable practices and innovation in offshore wind decommissioning, addressing competitive interests and aligning public perceptions with the complexities of resource management and market development.

While vessel cost and availability remained significant, stakeholders placed slightly less emphasis on these issues compared to the literature. Conversely, challenges related to port suitability and efficient dismantling, emerged as increasingly important.

Recommendations were thoroughly formulated to address key issues, including challenging recycling of composites and inadequate removal legislation.

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CRediT authorship contribution statement

J. Vetters: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **G. Thomassen:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **S. Van Passel:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 3.5 in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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