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Review

Marine biodiversity impact pathways for offshore wind farm decommissioning: Implications for Life Cycle impact assessment development

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ABSTRACT

The environmental conditions of the ocean are rapidly deteriorating in many locations, largely due to anthropogenic activities. Previous studies have indicated both negative and positive impacts on marine biodiversity during the construction and operation of OWFs, but the impacts of decommissioning remain largely unknown. Assessments of marine biodiversity impacts are now needed to support science-based decisions as the first OWFs are approaching decommissioning. Life Cycle Impact Assessment (LCIA) offers a quantitative and transparent approach to impact assessment but does currently not adequately cover marine biodiversity impacts. As a first step in developing an LCIA method, we conducted a systematic literature review to identify the links between offshore infrastructure decommissioning activities and their impacts on marine biodiversity. Links were delineated as impact pathways, providing the foundational framework for future LCIA development. We extended the scope of our study to oil and gas (O&G) platforms, given the similarities between the two types of offshore infrastructure and decommissioning activities. Our study identifies numerous impact pathways through which OWF decommissioning affects marine biodiversity. We found many similarities between impacts from the decommissioning of OWFs and O&G, but generally, more pathways were identified for O&G decommissioning. As the structures resemble each other, this study suggests that much knowledge can be brought from O&G decommissioning to OWF. We identified habitat change as particularly important when investigating impacts associated with offshore decommissioning, as several pressures may affect habitat change. The study also identified implications for developing a comprehensive LCIA method, including a scarcity of quantitative studies and empirical data, baseline definitions, as well as inconsistency in biodiversity metrics applied across reviewed studies. Importantly, the identified impact pathways provide the first step toward integrating marine biodiversity into LCIA in the context of the decommissioning of offshore structures.

1. Introduction

Human demands on sea space and maritime activities continue to expand rapidly across the globe, and this is expected to intensify in the coming decades (Moullec et al., 2021). Within Offshore Wind Energy (OWE) alone, the European Union plans to increase the capacity of OWE from 12 GW in 2022 to 300 GW by 2050 (Addamo et al., 2022). This would be an important step towards renewable energy transition and mitigating greenhouse gas emissions, but it could also have substantial impacts on marine biodiversity (European Environment Agency, 2018). In many locations, the environmental conditions of the ocean are deteriorating, and the main threats to marine ecosystems are related to

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human activities, including energy infrastructure (Halpern et al., 2019; United Nations Office of Legal Affairs, 2021). Therefore, it is essential that the anthropogenic use of the marine environment is balanced with biodiversity conservation.

Several studies have explored the negative and positive effects of OWE on marine biodiversity during construction and operation, including underwater noise and vibrations or the provision of hard substrate habitats (Degraer et al., 2020; Galparsoro et al., 2022; Lemasson et al., 2022; Macreadie et al., 2020; Wilson & Elliott, 2009). When Offshore Wind Farms (OWF) reach the end of their lifetime they will need to be decommissioned. The term "decommissioning" is here defined as the fate of a structure once it has reached the end of its operational lifetime, and the process of decommissioning can encompass different scenarios, including complete or partial removal of the structure (Claisse et al., 2015; Lemasson et al., 2021; Smyth et al., 2015; Sommer et al., 2019). By 2023, few OWFs have been decommissioned worldwide (4C Offshore, 2023), but the number of decommissioning projects will increase drastically in the coming years. In Europe alone, around 1,800 offshore wind turbines are expected to face decommissioning before 2030, and potentially 20,000 turbines between 2030 and 2040 (4C Offshore, 2023; Topham et al., 2019). There is currently a lack of experience and research in the field, so the impacts on marine biodiversity from OWF decommissioning remain largely unknown (Fowler et al., 2019; Lemasson et al., 2023; Watson et al., 2023). Furthermore, quantitative and transparent assessment methods for impacts on marine biodiversity associated with OWF decommissioning are lacking but are urgently needed to support science-based decisions around upcoming decommissioning projects (Dannheim et al., 2020; Lemasson et al., 2022; Li et al., 2023).

A method to enable science-based decisions is Life Cycle Assessment (LCA), as it provides scientifically based answers to questions regarding environmental impacts (Dong et al., 2017). LCA is widely used within research and industries to quantify the potential impacts of products and services on various environmental parameters such as climate change, ecotoxicity, and resource depletion. Regarding decision-making in industries and by regulators, LCA is highly beneficial as it synthesizes complex criteria into key indicators. Thereby, LCA communicates complex but important environmental measures in a simple and transparent manner. However, biodiversity metrics are underdeveloped in LCA, and existing Life Cycle Impact Assessment (LCIA) methods for biodiversity pressures, mainly cover terrestrial and freshwater ecosystems (Dorber et al., 2020; May et al., 2021; May et al., 2020; Souza et al., 2013; Verones et al., 2013; Winter et al., 2017). LCIA is the step of LCA in which elementary flows and processes (e.g., decommissioning-related processes) are translated and quantified into potential environmental impacts (Rosenbaum et al., 2018).

Only a limited number of impact pathways have been developed for impacts on marine biodiversity: Langlois et al. (2015) and Woods and Verones (2019) investigated and quantified impacts of seabed disturbance on ecosystems, and Middel and Verones (2017) quantified the impacts of underwater noise on cetaceans. Li et al. (2023) quantified the impacts of seabed occupation and the absence of trawling on macrobenthic organisms due to the existence of OWFs. Although these studies are relevant to OWF decommissioning, they are not expected to cover all of the impacts relevant to OWF decommissioning and consider only one or few species. While Lemasson et al. (2022) reviewed impacts on marine biodiversity associated with the presence and decommissioning of man-made structures, the authors only partially covered OWFs and did not operationalize findings for LCIA. In this context, operationalization refers to the process of facilitating the quantification of potential impacts from elementary flows and processes.

In this study, we take the first step towards developing an LCIA method for assessing impacts on marine biodiversity from various OWF decommissioning activities in temperate climate zones. As climate plays an important role for the benthic communities, affecting the species composition and richness, this study only targeted temperate climate zones (Agostini et al., 2020). Our approach is to undertake a systematic literature review of the current knowledge on marine biodiversity impacts from offshore structures (including oil and gas and other man-made structures) decommissioning to identify impact pathways linking decommissioning and the associated effects on marine biodiversity. Such impact pathways will form the basis for future LCIA method development. The desired LCIA method is intended for broad applicability among scientists, policy-makers, and stakeholders, emphasizing the necessity to communicate the impact pathways using widely understood terminology. The impact pathways are organized based on the DPSIR framework (D: Driving forces, P: Pressures, S: States, I: Impacts, and R: Responses) (Maxim et al., 2009), which is often used to structure communication between scientists and stakeholders like environmental managers or policy-makers (Borja et al., 2016; Maxim et al., 2009; Smyth et al., 2015), and has also been applied in relation to LCA (Chandrakumar & McLaren, 2018; Rugani et al., 2019). The European Environment Agency outlines DPSIR as a "causal framework for describing the interactions between society and the environment" (European Environment Agency, 2023). The pathways are also adjusted to the European Marine Strategy Framework Directive (MSFD) descriptors (European Commission, 2010). The MSFD includes 11 descriptors, which are specific criteria used to assess the environmental status of marine waters (European Commission, 2017). Based on our review findings, we outline the current limitations and the proposed next steps to developing an LCIA method for marine biodiversity impacts from OWF decommissioning.

2. Methodology

The reviewing process followed the systematic literature review protocol suggested by Pullin and Stewart (2006). The main research questions investigated in this study are: RQ1) What are the impacts of OWF decommissioning on marine biodiversity?, and RQ2) Which specific decommissioning activities form the causalities to the identified marine biodiversity impacts? To form the desired impact pathways, we needed publications that did not only state the impacts but also the causes of those. Therefore, we only considered publications that gave information on both RQs simultaneously.

2.1. Search terms

Search terms were developed to cover the study objectives and are listed in Table 1, where the asterisk (*) represents a search engine wild card. The wild card is used to represent any number of characters and is placed at the end of a root word to include variable endings of the root word. For instance, the results of a search on ecolog* would include words like ecology, ecological, and ecologic. The search terms from groups 1–5 were assembled to create a complex search string. To allow

Table 1
Search terms divided into groups (1–5). The asterisk (*) represents a search engine wild card.

1. **Offshore related terms**	offshore, sea, ocean, marine
2. **Ecosystem related terms**	biodiversity, species, ecolog*, ecosystem*, habitat*, mammal*, fish*, benth*, invertebrate*
3. **Structure related terms**	"wind farm*", "wind park*", "wind energy", "wind turbine*", "offshore wind", "wind power", windmill*, "offshore renewable*", scour*, rig*, platform*, "wind reef*", "artificial reef*", "man*made reef*", infrastructure*, substrat*, installation*
4. **Decommissioning terms**	decommission*, remov*, abandon*
5. **Negative keyword**	tropic*, subtrop*, Caribbean, "great barrier reef", arctic*, antarctic*, Mexic*

for a more comprehensive assessment, the study considered several offshore infrastructure types, such as oil and gas platforms and man-made artificial reefs (group 3), as these are expected to be comparable to OWFs in terms of marine biodiversity impacts from decommissioning (Lemasson et al., 2022). This study targeted temperate climate zones, and negative keywords (group 5) were used to exclude studies from tropic, subtropic, and arctic regions. Negative keywords are terms that are intentionally excluded from triggering the search, i.e., if the word “Caribbean“ is included as a negative keyword, this word will not trigger any hits in the search. The reason for scoping the study to temperate climate zones is that the climate plays an important role for the benthic communities, whereby species composition and richness are expected to vary largely in different climate zones. Generally, the natural benthic communities in high latitudes and temperate zones are dominated by macroalgae, while the natural benthic communities in lower latitudes, especially subtropical and tropical zones, are dominated by other ecosystems, such as coral reefs (Agostini et al., 2020). The search string was applied in March 2023 using two databases, Web of Science and Scopus, similar to previous studies (Flavio et al., 2017; Glarou et al., 2020). A cross-match of the results from each database was done to remove duplicates.

2.2. Screening and selection process

The papers extracted from the literature search were assessed for relevance at three sequential levels: title, abstract, and full text. The papers included in the analyses fulfilled the inclusion criteria listed in Table 2. Importantly, this study only considers species living underwater, thereby excluding birds and bats.

The search process resulted in 4771 papers (2615 sourced from Web of Science and 2156 from Scopus), of which 3651 remained after duplicate removal (Supplementary Material, Figure S1). In the review process, we specifically searched for papers supporting the development of impact pathways within the LCIA context. This means that the papers should not only indicate impacts (RQ1) but also the causes of those (RQ2). After reviewing the papers by title (3651 papers) and abstract (346 papers), 46 papers remained for full-text review. In this step, an additional 15 papers were added by searching papers connected to the full-text reviewed papers (“snowballing”) (Greenhalgh & Peacock, 2005), resulting in a total of 61 papers for full-text review. Finally, a total of 18 papers met the inclusion criteria (Table 2) and were suitable to meet the research objectives of our study.

2.3. Data extraction

The 18 papers were selected because they contained data on relations between removing one or more parts of a structure and an impact on an ecosystem-related element (see ‘Ecosystem related terms’ in Table 1). Data from the included papers were extracted and recorded in a spreadsheet (Supplementary Material). The recorded data included: spatial scale (e.g., the North Sea), publication year, structure type, physical characteristics of the structure (material and shape), investigated driving forces and pressures, and identified states and impacts.

Table 2
Inclusion and exclusion criteria for paper selection.

Criteria	Include	Exclude
Peer-review	Peer-reviewed studies	Everything else
Language	English	Everything else
Years	All years (−2023)	–
Location	Temperate areas	Everything else
Structure	OWFs, oil and gas installations, artificial reefs	Everything else
Subject	All underwater species (fish, mammals, benthic)	Everything above water (e.g., birds and bats)

Based on previous studies (Damiani et al. (2023), Maxim et al. (2009), and European Environment Agency (2023)), the DPSIR parameters were defined as specified in Table 3. Only a few papers (Burdon et al., 2018; Smyth et al., 2015) denote the terms of the DPSIR framework, and thus, the connections were formed based on an interpretation by the authors of the present study. Not all reviewed papers indicate all levels of the DPSIR framework, e.g., some studies do not indicate how the driving force leads to a pressure but merely indicate how the driving force leads to a state change or an impact.

2.4. Formulation of impact pathways

The extracted data were used to formulate impact pathways by connecting activities related to structure removal to the pressures, states, and impacts described in the respective reviewed papers. In cases where not all levels of the DPSIR framework are indicated (e.g., missing a pressure), the developed impact pathways go directly from driving force to state or impact. The identified pressures, states, and impacts were formulated according to the 11 MSFD descriptors: D1. Biological diversity, D2. Non-indigenous species, D3. Exploited fish and shellfish, D4. Food webs, D5. Human-induced eutrophication, D6. Seafloor integrity, D7. Hydrographical conditions, D8. Contaminants, D9. Contaminants in fish and seafood, D10. Litter, and D11. Energy and noise (Borja et al., 2013; European Commission, 2010). The pressures, states, and impacts are not related to the MSFD descriptors in the reviewed papers, and thus, the linkage was made based on an interpretation by the authors of the present study. The MSFD descriptors relate to different parameters of the DPSIR framework, e.g., energy and noise (D11) relate to pressures, while hydrographical conditions (D7) relate to changes in states. Other descriptors can be related to multiple DPSIR parameters, e.g., seafloor integrity (D6), which is related to pressures and states, or biological diversity (D1), which is related to states and impacts. In this study, a range of criteria are also considered under the biodiversity descriptor (D1), including species distribution (D1.1.), population size (D1.2.), population condition (D1.3.), habitat distribution (D1.4.), habitat extent (D1.5.), and habitat condition (D1.6.). D1.1.-D1.3. are considered as impacts, while D1.4.-D1.6. are considered as state conditions in the present study.

3. Results

A summary of the 18 papers included in the analysis is given in Table 4. Further information is available in the Supplementary Material. Seven different pressures, six state changes, and six impacts were identified in the 18 papers (Table 4). Some papers merely state impacts

Table 3
The definitions of DPSIR parameters (Driving force, Pressure, State, Impact, Response) used in this study. Definitions are based on Damiani et al. (2023), Maxim et al. (2009), and European Environment Agency (2023).

Driving force	Driving forces are anthropogenic activities and processes causing pressures. In this study, the driving forces were related to offshore decommissioning.
Pressure	The physical result of a driving force that affects the state of the environment, e.g., an elementary or energetic emission to the environment, such as vibrations or sediment disturbance.
State	The quantity and quality of physical phenomena (such as temperature), biological phenomena (such as fish stocks), and chemical phenomena (such as contamination concentrations) in a certain area.
Impact	A change in the physical, chemical, or biological state of the environment which determines a modification in the quality of ecosystems.
Response	Responses refer to actions or decisions made to control Driving forces or Pressures (prevention or mitigation), to maintain or restore the State of the environment, to help accommodate Impacts (adaptation), or even deliberate “do nothing” strategies (Maxim et al., 2009). Responses are not considered in this study.

Table 4
Summary of papers included in the analysis. Abbreviations for structure type: oil and gas platform (O&G), offshore wind farm (OWF). Abbreviations used for pressures: contamination (C), sediment disturbance (D), introduction or spread of invasive species (I), introduction of light (L), seafloor conservation (S), underwater noise (U), vibration (V). Abbreviations used for states: connectivity conditions (Co), food web conditions (Fo), habitat extent and conditions (Ha), hydrographical conditions (Hy), remobilized contaminants (Re), seafloor integrity (Se). Abbreviations used for impacts: species abundance (Abu), biomass (Bio), physical damage to species (Dam), endangered species (End), species reproductivity (Rep), and species richness (Ric).

Paper	Geography	Structure type	Driving Forces	Pressures	States	Impacts
Bomkamp et al. (2004)	California	O&G	Complete removal		Ha	Abu
Gill (2005)	Unspecified	OWF	Complete removal	D, U, V	Fo, Ha, Hy, Re, Se	Dam, Rep
Martin and Lowe (2010)	California	O&G	Partial removal		Ha	Abu, Bio
Claisse et al. (2015)	California	O&G	Partial removal		Ha	Bio, Rep
Pondella et al. (2015)	California	O&G	Complete and partial removal; Explosives			Bio, Dam
Smyth et al. (2015)	North Sea	OWF	Complete and partial removal	D, U	Fo, Ha, Hy	Bio
Kaldellis et al. (2016)	Multiple areas	OWF	Complete removal	U, V	Ha, Re	Dam, Ric
Burdon et al. (2018)	United Kingdom	O&G	Complete removal; Vessel operation	C, D, I, L, U, V,	Ha, Hy, Re	Abu, Dam, Rep
Elden et al. (2019)	Multiple areas	O&G	Partial removal	I, S	Se	Bio, End, Ric
Fowler et al. (2019)	North Sea	O&G, OWF	Complete and partial removal	D, S	Co, Ha, Re, Se	Bio, End, Rep, Ric
Meyer-Gutbrod et al. (2019)	California	O&G	Complete and partial removal		Fo, Ha	Abu
Sommer et al. (2019)	Multiple areas	O&G	Complete and partial removal	C, S	Co, Ha, Se	Bio
Coolen et al. (2020)	North Sea	O&G	Complete removal		Ha	Ric
Fortune and Paterson (2020)	Multiple areas	O&G, OWF	Complete removal; Explosives	U	Ha	Bio, Dam
Meyer-Gutbrod et al. (2020)	California	O&G	Complete and partial removal		Ha, Se	Bio, Rep
Tidbury et al. (2020)	North Sea	O&G	Complete removal		Co, Ha	Abu, End
Gusatu et al. (2021)	North Sea	OWF	Complete removal	V	Fo, Ha, Re	Abu
Hall et al. (2022)	Unspecified	OWF	Complete removal; Introduction of new material; Vessel operation	D, U	Ha, Hy, Re	Bio, Dam, End

from a driving force and do not indicate the associated pressures or state changes. In such cases, the table cells remain blank. The driving forces contained in the papers are either the removal of the structure itself (complete or partial) or activities related to the removal of the structure, such as using explosives, vessel operation, or introducing new materials to fill voids. In most cases, complete removal entails the removal of all structural components, cables/pipes, and scour protection. However, many studies do not specify exactly how much of the installation is removed in case of complete removal (Fortune & Paterson, 2020; Fowler et al., 2019; Gusatu et al., 2021; Kaldellis et al., 2016; Sommer et al., 2019). If the structural elements are buried in the seabed, some studies consider the full removal of the parts in the seabed (Smyth et al., 2015), but again, many do not report these details. In most cases, partial removal entails the removal of the structural parts (e.g., platform) to a depth of 25 or 26 m from the water surface to comply with navigational safety (Claisse et al., 2015; Martin & Lowe, 2010; Meyer-Gutbrod et al., 2020; Pondella et al., 2015; Sommer et al., 2019). However, some studies also investigate other options for partial removal, such as removal of the superstructure only ("topping"), laying down the structure on the seafloor ("toppling"), removal from the seafloor and up, or leaving only some of the scour protection in place (Coolen et al., 2020; Elden et al., 2019; Fowler et al., 2019; Smyth et al., 2015; Sommer et al., 2019).

4. Research trend

Fig. 1 shows the topics contained in the 18 papers included in the analysis. The topics are gathered in categories covering publication year, geographical scope, structure type, investigated pressures, and identified states affected. The sum of numbers in one category, or even within one state change, can deviate from the total number of papers included in the analysis (18), as each study can cover multiple pathways, pressures, and state changes. For instance, 'habitat extent and conditions' (state) exceed 20 papers, as some papers investigate multiple pathways to habitat changes.

All papers collected for full-text review were published after 2003, and among the papers included in the study, 15 were published within the last ten years. When investigating geographical areas with temperate climate zones, the North Sea and California are covered the most. No OWFs exist in California, and therefore oil and gas platforms are the only structures investigated in this area (4C Offshore, 2023). The geographical category 'Multiple areas' includes studies investigating more locations, often globally, whereas the category 'Unspecified' includes studies that take a global perspective and do not mention specific areas examined. The study from the United Kingdom does not specify in which sea surrounding the United Kingdom the investigated oil and gas platforms are located, and it is placed in its own category.

Eleven reviewed papers investigated oil and gas platforms, five investigated OWFs, and two investigated 'Mixed' structures. The structure category 'Mixed' includes studies that considered both oil and gas and OWFs (Fowler et al., 2019) and studies where the structure is described as 'man-made structures' (Fortune & Paterson, 2020). Due to the limited number of OWFs decommissioned (4C Offshore, 2023), only a few studies were found on the topic. More studies were identified for oil and gas as more have been decommissioned (Elden et al., 2019). Many OWF structures are similar to oil and gas platforms regarding the structural design and materials used (e.g., steel monopile or jackets). They are, therefore, comparable in terms of marine biodiversity impacts (Lemasson et al., 2022). However, there are also essential differences worth considering when comparing the two structure types. For example, oil and gas platforms have typically been constructed in deeper waters and further offshore, and a platform has a larger footprint on the seafloor compared to a single offshore wind turbine foundation. Regarding spatial arrangement, oil and gas platforms are rarely arranged close to each other in farms, like wind turbines are. Additionally, oil and gas processing platforms often discharge contaminants during their operational lifetime, which may accumulate in the seabed and possibly remobilize when decommissioning (Ekins et al., 2006).

The pressures investigated include specific pressures like underwater noise, vibration, and sediment disturbance, while some studies merely

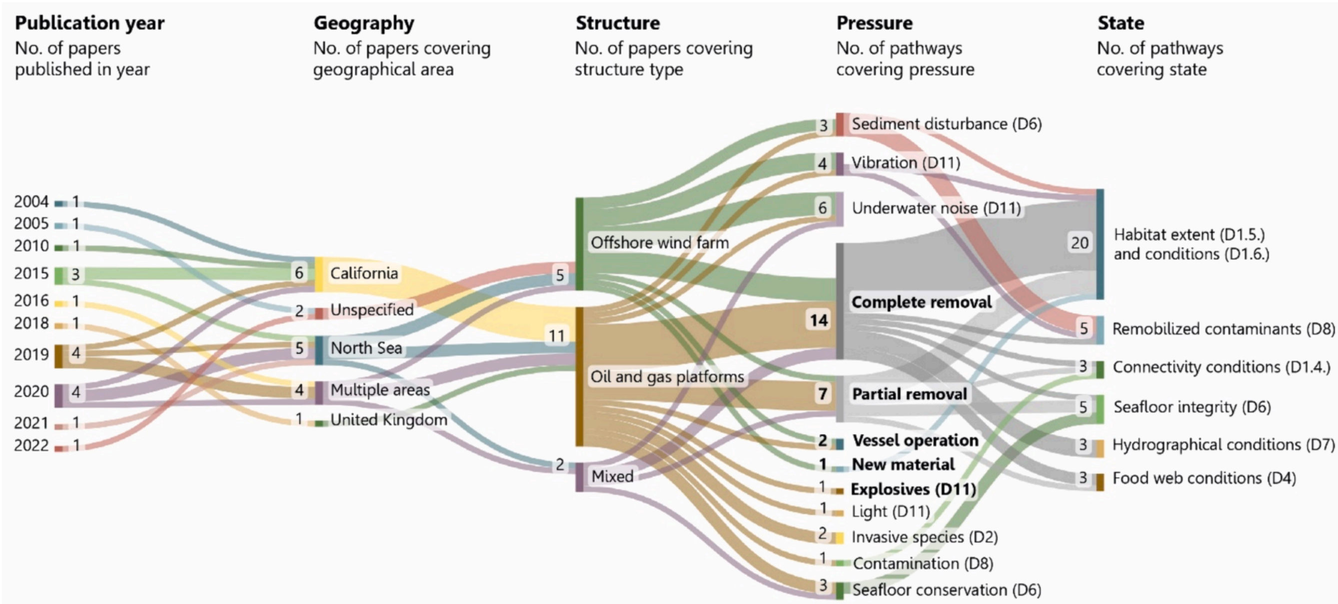

Fig. 1. Sankey diagram reflecting the number of publications covering different publication years, geographical areas, and structure types. Furthermore, the number of pathways identified in the reviewed literature covering different pressures and states. Some driving forces (written in bold) are listed together with pressures to account for the studies that do not indicate pressures. The MSFD descriptor relevant to the respective pressure or state is indicated with a "D" followed by a number referring to the descriptor number (Borja et al., 2013; European Commission, 2010).

report the removal of structure (driving force). Structure removal can lead to direct impacts on biodiversity, including physical removal of organisms growing on the structure, but can also lead to pressures that will cause state changes, e.g., sediment disturbance leading to habitat change and vibrations leading to remobilization of contaminants from the seafloor.

4.1. Impact pathways

Based on the reviewed literature, impact pathways were developed, linking driving forces associated with decommissioning activities to pressures, state changes, and impacts on marine biodiversity. The pathways are illustrated for oil and gas platforms in Fig. 2A and for OWFs in Fig. 2B. Some of the pressures and impacts listed in Table 4 and Fig. 1 have been collected in the MSFD descriptors they belong to. This concerns *D11 Introduction of energy* (underwater noise, vibration, and introduction of light), *D6 Sediment disturbance* (seafloor conservation and sediment disturbance), *D1.1. Species richness* (endangered species and species richness), and *D.1.2. Species abundance* (biomass, physical damage to species, and species abundance). Importantly, the developed impact pathways reflect the pressure-impact links covered in the reviewed literature and not an exhaustive list of all impact pathways possible. Furthermore, the study includes locally induced impacts on marine biodiversity, whereas globally or regionally induced impacts, such as impacts on marine biodiversity from climate change, are omitted.

Many impact pathways identified for OWFs resemble those identified for oil and gas platforms. Common for the two structures is that many studies have identified changes to the state 'habitat extent and conditions' from decommissioning activities. 'Habitat extent and conditions' can be affected by several pressures, e.g., sediment disturbance, vibrations (energy), or even directly from the structure removal. This indicates that habitat change is particularly important when investigating impacts associated with offshore structure decommissioning. Despite the many similarities in the pathways identified for OWF and oil and gas platforms, some differences occur. Generally, more pressures were identified for decommissioning of the oil and gas structures than OWF structures. This includes contamination associated with dismantling and the introduction of invasive species associated with transportation activities. The use of explosives as a driving force is only identified for oil and gas platform decommissioning, and 'connectivity conditions' as a state change is the only identified for oil and gas platform decommissioning.

The review identified impacts on a range of MSFD descriptors: biological diversity (D1), invasive species (D2), food webs (D4), seafloor integrity (D6), hydrographical conditions (D7), contaminants (D8), and introduction of energy (D11). Under the biodiversity descriptor (D1), a range of criteria was identified for the impacts, such as species distribution (D1.1.), population size (D1.2.), or population condition (D1.3.). The MSFD biodiversity descriptor also includes criteria for habitat distribution (D1.4.), extent (D1.5.), and condition (D1.6.), defined as state conditions in the present study. This range of biodiversity metrics illustrates how many aspects the term biodiversity covers and underlines the multitude of ways of understanding and interpreting biodiversity.

The illustrated impact pathways can form the first step in developing LCIA methods covering impacts on marine biodiversity associated with decommissioning OWFs or similar structures in temperate climate zones. However, only a few of the reviewed studies include a quantification of the pathways, and such quantifications are based on case studies and have not been brought to a more general level. This applies to studies having quantified the impacts on fish reproductivity, abundance, or biomass from the full or partial removal of oil and gas structures (not connected by pressures in reviewed studies) (Claisse et al., 2015; Martin & Lowe, 2010; Meyer-Gutbrod et al., 2020; Pondella et al., 2015). Furthermore, a single study has quantified the loss of macrofaunal species richness from decommissioning a concrete gas platform (Coolen et al., 2020). Few studies investigated impacts on marine mammals (physical damage) from noise (Gill, 2005; Hall et al., 2022; Kaldellis et al., 2016), and a single study investigated impacts on mussels from full or partial removal of structure (Meyer-Gutbrod et al., 2019). However, the impacts on mammals and mussels have not been quantified. In general, fish are the most studied organisms when it comes to impacts from decommissioning OWFs and oil and gas structures in temperate regions.

Mainly negative impacts (loss of biodiversity) have been reported in the reviewed studies and included in the developed impact pathways.

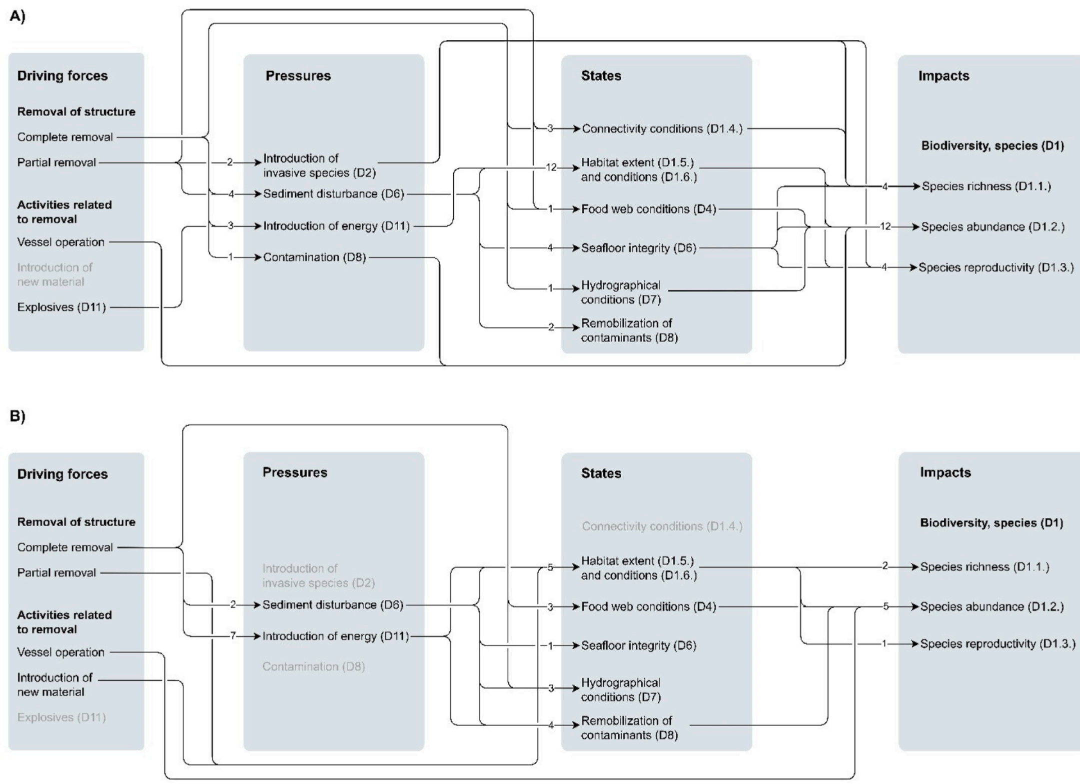

Fig. 2. The impact pathways identified for oil and gas platforms (A) and OWFs (B), ordered according to the DPSIR framework (European Environment Agency, 2023). The MSFD descriptor relevant to the respective pressure, state, or impact is indicated with a "D" followed by a number referring to the descriptor number (Borja et al., 2013; European Commission, 2010). The numbers on the arrows indicate the number of reviewed studies investigating the specific pressure/state/impact. The words written in grey were not identified for the structure illustrated but were identified for the other type of structure.

The partial removal of offshore structures allows the area to act as an exclusion zone, where trawl fishing is not allowed (Elden et al., 2019; Sommer et al., 2019). This can create positive effects on seafloor integrity (state) and thereby positively affect marine biodiversity because the area and habitats will remain protected from the physical damage caused by fishing. Other positive effects relate to the potential of reusing or recycling materials from the decommissioned structure. For example, Fortune and Paterson (2020) reported that 95 % of wastes from decommissioning man-made structures on the United Kingdom Continental Shelf were reused or recycled in 2015. Such impacts are, however not considered in this study, as the review focuses on impacts on marine biodiversity.

5. Discussion

The knowledge of the impacts of OWF decommissioning on marine biodiversity is limited, and research and quantitative assessment tools are needed to support upcoming decommissioning projects. As highlighted by Watson et al. (2023) and Topham et al. (2019), there is a need to better understand and quantify the impacts of decommissioning activities on marine ecosystems if ecological aspects should be comprehensively considered in the decision-making around decommissioning. This systematic literature review compiled the current knowledge and identified impact pathways for decommissioning OWFs and oil and gas platforms and the associated impacts on marine biodiversity, thereby establishing the first step toward developing an LCIA method. Common for the OWF and oil and gas structures is that many pathways are connected to the state 'habitat extent and conditions'. 'Habitat extent and conditions' can be affected by several pressures, such as 'Sediment disturbance (D6)' and 'Introduction of energy (D11)', or even directly by the removal of structure. The type of habitat change associated with decommissioning would typically be from hard substrates (steel, concrete, rocks) to soft substrates (sand). Furthermore, removing the vertical structure (fully or partially) would entail removing a hard substrate habitat from the water column (Gill, 2005; Smyth et al., 2015). The magnitude of biodiversity impacts from these habitat changes is yet to be analyzed, but the findings of this study indicate that habitat change is particularly important when assessing impacts on benthic communities (Bomkamp et al., 2004; Gill, 2005; Kaldellis et al., 2016; Smyth et al., 2015). Therefore, this study proposes that habitat change be used as a starting point in developing an LCIA method for OWF decommissioning and the associated impacts on marine biodiversity. For the LCIA method to be comprehensive, it is necessary to investigate and include all driving forces, pressures, and state changes associated with OWF decommissioning that impact marine biodiversity. The oil and gas industry may provide some valuable insights into this due to its larger experience with decommissioning.

5.1. Learnings from oil and gas decommissioning

Based on similarities identified between oil and gas and OWF decommissioning, the oil and gas industry's experience in decommissioning can provide valuable insights for OWF decommissioning. Oil and gas studies cover several pressures expected to be relevant to OWFs. These pressures include the introduction of light from machinery used for decommissioning activities, contamination, introduction of invasive species, and seafloor conservation. The pressure 'contamination' is expected to be much larger at oil and gas sites due to the risk of discharge from produced water or other hazardous chemicals (Marappan et al., 2022), but some contamination can occur from OWF decommissioning. When a wind farm is decommissioned, there is a risk of chemical pollution, which mainly involves the risk of spilled oil or resin that is present within the wind turbine (Teunis et al., 2021; Topham et al., 2019). The pressure of introducing invasive species covers more aspects:

firstly, the connectivity aspect of removing or leaving the structure, which affects the connectivity with other reefs (natural or artificial) and thus the risks of creating passages for invasive species (Lemasson et al., 2022; McLean et al., 2022). This may be influenced over time when more OWFs and other structures are being constructed and decommissioned. As for oil and gas platforms, the decommissioning of OWFs may involve different scenarios ranging from full removal to leaving parts of the structure in place, which will affect the presence of invasive species (Burdon et al., 2018; Kerkvliet & Polatidis, 2016). Secondly, there is a risk of spreading invasive species during transportation (Teunis et al., 2021). This could be ship transportation of elements to shore over longer distances or in case of transporting the structure for reefing elsewhere (Elden et al., 2019; Sommer et al., 2019). The use of explosives as a driving force and 'connectivity conditions' as a state change was identified for oil and gas decommissioning but not for OWF. Explosives are rarely considered for OWF decommissioning and can be disregarded. However, the conditions for connectivity and introduction of invasive species are just as relevant to OWFs as it is to oil and gas, as it concerns how the structure relates to other reefs in the ocean.

Smyth et al. (2015) is the only OWF study investigating partial removal. They consider leaving the scour protection in place but not leaving larger parts of the monopile. Most partial removal options for oil and gas platforms concern removal until a depth of 25–26 m from the water surface. As most of the existing OWFs are not constructed in such deep waters (4C Offshore, 2023), this scenario will not be possible for most of the OWFs present today. However, removal until other depths (e.g., 12 m from the water surface) could be considered for OWFs in shallower waters.

5.2. The time aspect of impacts

The time scale of impacts is important to consider when going forward with the LCIA model development. Whereas some pressures may only cause short-term impacts from which the ecosystem can recover, other pressures are likely to cause more permanent long-term impacts. An example of a pressure causing short-term impacts is the introduction of energy associated with decommissioning activities (noise, vibrations, and light), which may result in a temporary loss of habitat and a temporary loss of individuals within that habitat (Middel & Verones, 2017). Sediment disturbance is an example of a pressure that can cause impacts on different time scales. It can cause impacts that disturb the habitat temporarily but do not change the habitat type, e.g., soft sediment habitat remains soft sediment, but the benthic species need to recover after disturbance (Kaldellis et al., 2016). Sediment disturbance can also cause long-term impacts if the habitat type is more permanently changed, e.g., from hard substrates to soft substrates, which means that the habitat may not be able to host the same species as before. Both short- and long-term impacts can be modeled in LCIA, but it is necessary to consider if the changes will be temporary or permanent, and how much time it may take for the habitat to reach a stable state of biodiversity.

5.3. Establishing a baseline

To assess the impacts of an activity or a change, a baseline needs to be established (Borja et al., 2012). Among the reviewed studies, many do not state which baseline their assessment is compared to, but those studies that assessed impacts quantitatively used the state just before decommissioning as a baseline. For an OWF, the baseline can be defined in different ways; it could be the state of biodiversity in the OWF 1) just before decommissioning, 2) at a nearby reference site or just before constructing the OWF, typically, 25–35 years before decommissioning, or 3) before any human activities took place in the area (i.e., pristine conditions), typically more than 150 years ago in most European seas (Coolen, 2017). Considering the change that has occurred in the coastal water of the North Sea or Baltic over the last centuries, this could potentially translate to a baseline ranging from 1) a well-established artificial stone reef habitat and its associated community, 2) heavily disturbed sand bed, or 3) pristine biogenic and rock reef and their associated communities (Coolen, 2017; Olsen, 1883).

A baseline must be chosen to develop an LCIA method for marine biodiversity impacts from OWF decommissioning (Koellner & Scholz, 2006; Li et al., 2023; Milà i Canals et al., 2006). We expect that the choice of baseline is likely to impact the outcome of the LCIA greatly; thus, disclosing baseline information will be critical in the context of LCIA. For example, the level of biodiversity is expected to decrease both in case of partial and complete removal if the extent of habitat is related to the pre-decommissioning stage or a habitat with a high level of biodiversity (e.g., pristine). But if relating the post-decommissioning state to the state just before construction, the case of partial removal might show an increase in biodiversity. In this context, it is also important to note that an increase in biodiversity is not always positive (Spielmann et al., 2023; Zupan et al., 2023). The outcome depends on the species composition and the desired target. If the target is the pristine ecosystem, then a gain of species is only positive if it is those included in the pristine ecosystem. This study recommends that baseline options should be discussed among field experts and preferably that a common agreement is reached regarding a suitable baseline.

5.4. Positive impacts and burden shifting

The positive impacts (increase in biodiversity) included in the reviewed literature are limited and mainly relate to seafloor conservation or the possibility for the area to act as an exclusion zone where trawl fishing is typically not allowed (Elden et al., 2019; Sommer et al., 2019). The latter concerns the post-decommissioning usage of the area, which can span over many years. As it does not reflect an immediate effect on marine biodiversity, it is not included in the developed impact pathway diagrams. However, as the environmental conditions of the ocean are deteriorating in many areas, caused by anthropogenic activities (United Nations Office of Legal Affairs, 2021), there is an urgent need to protect and conserve global marine areas. By 2030, the Kunming-Montreal Global Biodiversity Framework states that at least 30 % of the global degraded marine ecosystem areas should be under effective restoration, and at least 30 % should be effectively conserved (European Commission, 2022; United Nations, 2022). After some OWFs have served as exclusion zones for many years, extending the exclusion period is an evident possibility for preserving the ecosystems. The potential positive and negative impacts of such exclusion zones should, therefore, be further investigated for areas with decommissioned OWFs. Furthermore, considering the scale of the impact is crucial. Whether an impact can be considered positive depends on the scale of the assessment. Closing one area for fish trawling may displace the activity to other regions, potentially shifting the burden. In such cases, the local impact would be assessed as positive, while the regional or global impact might not be positive.

5.5. Limitations for LCIA development

The lack of data is the main limitation identified for developing the desired LCIA method. Decommissioning of OWFs is a new field of practice in the industry and a new field of research, and limited experience is available. Most of the reviewed studies are qualitative, and quantitative measures of the impacts are missing. For OWFs, no quantitative studies were identified. In terms of oil and gas structures, the quantitative studies mainly investigated impacts on fish reproductivity, abundance, or biomass from the full or partial removal of oil and gas structures without linking it to pressures or state changes (Claisse et al., 2015; Coolen et al., 2020; Martin & Lowe, 2010; Meyer-Gutbrod et al., 2020; Pondella et al., 2015), and one study quantified the loss of macrofaunal species richness from decommissioning a concrete gas platform (Coolen et al., 2020).

Another limitation identified is the inconsistency in biodiversity metrics. Specifically, biodiversity can be defined at three levels: genetic, species, and ecosystem diversity (United Nations, 1992), and just within species diversity, many different metrics are used: species richness is used to express the number of species present in the assessed area and species abundance is used to estimate the number of individuals within a species. Furthermore, several of the reviewed studies use biomass as a measure or reflect the impacts on endangered species or species reproductivity. In LCA, impacts on the natural environment are commonly expressed using the unit Potentially Disappeared Fraction of species (PDF), which is presented as the mean change in species richness relative to a local reference site within a known area and time frame (unit: PDF x m^3 x yr) (Goedkoop et al., 2022). PDF is a convenient metric in the LCA framework as it can be calculated across taxonomic groups (e.g., birds, fish, plants) and environmental compartments (e.g., land, freshwater, marine), but is also associated with some limitations (Verones et al., 2022). For instance, the PDF metric solely concentrates on species richness, thereby neglecting the characterization of potential damage to ecosystem function, i.e., ecosystem processes, and/or structure, i.e., the physical attributes of ecosystems (Curran et al., 2011; Woods et al., 2018; Woods et al., 2016). Furthermore, the existence of non-linear ecological responses to pressures is a challenging issue in the context of LCIA models, which are based on the assumption of linear stress-response functions (Huijbregts et al., 2011).

Based on the outlined limitations, this study highlights the essential research and discussions needed to develop the desired LCIA method (Fig. 3). Firstly, this study highlights a need to collect empirical data around OWFs. To estimate the immediate impacts of decommissioning, data should be collected both before and after decommissioning, e.g., using a Before-After Control-Impact (BACI) study (Kerr et al., 2019; Wilms et al., 2021). To quantify the long-term impacts of decommissioning and the recovery time, data should be gathered continuously in the years after decommissioning and throughout the entire lifetime of the OWF, as this will help establish a baseline and understand the development of the ecosystem in the OWF. Data should also be gathered from nearby control sites to establish a shifting baseline accounting for the ecosystem changes from other physical parameters such as changes in salinity, eutrophication, and temperature. Additionally, this study recommends starting the LCIA development by incorporating impacts from habitat change, as this was identified to be particularly important when assessing biodiversity impacts associated with offshore structure decommissioning. This means that empirical data collection should be focused on habitat change as a beginning. Furthermore, the present study recommends a globally focused discussion on biodiversity metrics to reach a common understanding and agreement on metrics, which is essential to enable comparison of different studies. The desired metric(s) should capture the important aspects of biodiversity and at once be comparable and applicable in LCIA.

6. Conclusion

This systematic literature review identifies impact pathways for activities related to the decommissioning of OWFs and the associated impacts on marine biodiversity. It forms the first step for developing an LCIA method to quantify impacts on marine biodiversity from decommissioning of OWFs. Due to a globally limited experience with OWF decommissioning, we included the decommissioning of other offshore structures, particularly oil and gas platforms. While more impact pathways were identified for oil and gas decommissioning than for OWFs, similarities identified between oil and gas and OWF structures and decommissioning processes suggest that data and knowledge could potentially be transferred from the oil and gas studies to OWF decommissioning. The review clarified that OWF decommissioning affects marine biodiversity through various impact pathways and highlighted habitat change as particularly important when investigating biodiversity

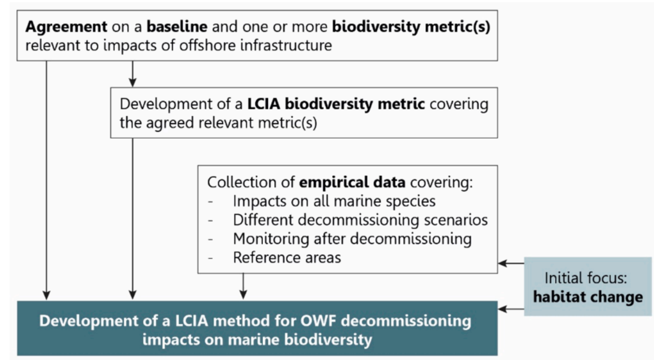

Fig. 3. Conceptual figure outlining the required input to develop a comprehensive LCIA method for OWF decommissioning impacts on marine biodiversity. The figure also illustrates the proposed initial focus for data collection and LCIA method development.

impacts associated with offshore structure decommissioning. Therefore, this study proposes that the future development of an LCIA method should focus on habitat change as a start. Nevertheless, several implications for developing a comprehensive LCIA method emerge, including a scarcity of quantitative studies and empirical data and the inconsistency in biodiversity metrics applied across reviewed studies. In addition, the limited number of papers (18) identified in this systematic literature review indicates that the knowledge base is still limited and will require expansion to ensure that all impact pathways are identified and to support the development of a comprehensive LCIA method. Moreover, the study emphasizes the need to address the selection of a baseline against which to compare the state of biodiversity post-decommissioning, recognizing the substantial influence this choice is expected to have on the results of the LCIA.

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CRediT authorship contribution statement

Liv Stranddorf: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Tracey Colley:** Writing – review & editing, Supervision. **Matthieu Delefosse:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jon C. Svendsen:** Writing – review & editing, Supervision, Methodology. **Stig Irving Olsen:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Liv Kristensen Stranddorf reports financial support was provided by the Danish Innovation Fund. Jon C. Svendsen reports financial support was provided by Vattenfall. Other 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.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112613.

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