Environmental Impact Assessment Review 118 (2026) 108253

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Evaluating environmental impacts and public preferences in offshore wind farm decommissioning

Liv Stranddorf[a,b,c,*], Jacob Ladenburg[d], Agnes Rönnblom[e], Lena Landström[e], Stig Irving Olsen[a,c]

[a] Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark (DTU), Bygningstorvet, Building 115, 2800 Kgs. Lyngby, Denmark
[b] Environment and Sustainability Unit, Vattenfall Vindkraft, 6000 Kolding, Denmark
[c] Centre for Absolute Sustainability Assessment, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark
[d] Climate and Energy Policy Division, Department of Technology, Management and Economics, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark
[e] Corporate Environment, Vattenfall AB, Evenemangsgatan 13, 169 79 Solna, Sweden

ARTICLE INFO

Keywords:
Offshore wind energy decommissioning
Life cycle assessment
Marine biodiversity
Social acceptance
North Sea case study

ABSTRACT

The expansion of offshore wind energy presents new challenges as many wind farms approach the end of their operational lives and will need to be decommissioned. This study presents the first multi-criteria assessment of offshore wind farm decommissioning scenarios that brings together life cycle environmental impacts, local marine benthic biodiversity impacts, and public preferences. Using Horns Rev 1 – the oldest large-scale wind farm in the North Sea - as a case study, we analyze 16 decommissioning scenarios ranging from full removal of infrastructure to partial removal strategies in which parts of the foundation, scour protection, or cables are left in place. Environmental impacts are assessed through life cycle assessment, and local marine biodiversity impacts are quantified using a newly developed method tailored to North Sea habitats. Public preferences are analyzed based on a nationally representative Danish survey. Our findings show that removing high-value recyclable materials while leaving scour protection in place yields the lowest life cycle environmental impacts due to recycling benefits and avoided removal of components with low recycling value. In contrast, full removal receives the strongest public support and best aligns with restoration of the sandy seabed but also results in higher climate impacts. Biodiversity outcomes depend on the selected reference state and desired ecological function, with trade-offs between supporting native benthic communities and preserving artificial reef structures that support diverse communities. This study demonstrates the value of a multi-criteria approach to offshore wind decommissioning and provides a transferable framework supporting decision-making by integrating environmental, ecological, and societal dimensions.

1. Introduction

The transition to a low-carbon energy system is central to mitigating climate change, and offshore wind energy is playing an increasingly important role in this transformation. The European Union aims to expand the offshore wind capacity from around 20 GW in 2023 to over 300 GW by 2050 (European Commission, 2020), with much of this growth concentrated in the North Sea (Henley, 2023; Machado and de Andrés, 2023). As the offshore wind sector matures, a growing number of wind farms are reaching the end of their operational life, and attention is turning to decommissioning. Among these, several of the oldest large-scale Offshore Wind Farms (OWFs) are located in the North Sea, and this region is thus at the forefront of this emerging challenge. Decommissioning refers to the actions taken when a structure reaches the end of its use phase, ranging from dismantling and removal of all elements to leaving substantial components in place on the seabed (Spielmann et al., 2023).

Experience with OWF decommissioning remains limited, as only a few wind farms have been decommissioned to date (Adedipe and Shafiee, 2021). In the North Sea, decommissioning is formally governed by the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission, 1998), which generally

* Corresponding author at: Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark (DTU), Bygningstorvet, Building 115, 2800 Kgs. Lyngby, Denmark.
E-mail address: livks@dtu.dk (L. Stranddorf).

https://doi.org/10.1016/j.eiar.2025.108253
Received 24 August 2025; Received in revised form 23 October 2025; Accepted 28 October 2025
Available online 31 October 2025

requires full removal of all offshore installations. However, the convention allows national authorities to grant exemptions if environmental protection and maritime safety can be ensured. In Denmark, national legislation does not prescribe specific requirements for OWF decommissioning, leaving room for case-by-case decisions, including the possibility of partial removal. As a result, developers and regulators are now faced with complex decisions that should balance legal obligations, technical feasibility, environmental impacts, and broader societal considerations, including public attitudes toward different decommissioning approaches.

From an ecological perspective, OWFs alter the marine environment by introducing hard substrates such as steel foundations and scour protection stones into predominantly soft-bottom seabed habitats. These structures are often colonized by marine organisms, forming artificial reef-like habitats that can potentially enhance local biodiversity (Degraer et al., 2020; Galparsoro et al., 2022; Hall et al., 2020). As a result, complete removal of OWFs may eliminate habitats that have become ecologically valuable over time, raising questions about whether full removal and restoration to pre-installation conditions is always the most environmentally beneficial outcome. Life Cycle Assessment (LCA) is a commonly used tool to evaluate the environmental performance of OWFs across their life cycle (Bonou et al., 2016; Wagner et al., 2011). However, recent studies show that most existing LCA studies treat the decommissioning phase with limited detail. This may reflect both limited data availability and differences in the scope of study. Often, studies consider only one decommissioning alternative, assuming full removal of all components (Bonou et al., 2016; Demuytere et al., 2025) or full removal of foundations while leaving scour protection in place (De Luca Peña et al., 2024). In general, marine biodiversity impacts are typically excluded from LCA due to the lack of suitable impact assessment methods. To address this gap, a new Life Cycle Impact Assessment (LCIA) method has recently been developed to assess changes in local benthic biodiversity based on habitat transformation (Stranddorf et al., 2025b). While the method provides a novel approach for quantifying marine biodiversity impacts associated with the construction and decommissioning of OWFs, it has not yet been applied in any published case studies.

In parallel with these environmental considerations, the social dimension of decommissioning has received far less attention. Public support has long been a critical factor in the siting and acceptance of renewable energy infrastructure, and similar considerations are likely to shape decommissioning decisions (Fowler et al., 2018; Glasson et al., 2022; Watson et al., 2023). Historical cases, such as the controversy of decommissioning the oil platform *Brent Spar* in the 1990s, demonstrate that strong public opposition may influence the decisions related to decommissioning: despite regulatory approval and scientific justification to leave structural elements in place, public protests forced a reversal of offshore decommissioning plans and triggered changes to policy frameworks (Bate, 1995). While Vetters et al. (2025) assessed stakeholder perspectives on OWF end-of-life challenges, no studies have, to our knowledge, investigated how the public perceives different decommissioning options for OWFs. In particular, it is unclear whether there is public support for leaving certain components in place, especially when weighed against environmental aspects. Given the increasing emphasis on stakeholder involvement and social license to operate in the wind industry (Johansen, 2019; Stephens and Robinson, 2021), understanding public preferences is essential for ensuring that future decommissioning decisions are not only technically and environmentally sound but also socially acceptable.

Despite the growing need to plan for OWF decommissioning, existing research remains fragmented, and no studies have yet brought together LCA-based environmental assessments, including biodiversity and social acceptance, into investigations of decommissioning options. Prior reviews emphasize that the majority of environmental assessments neglect the decommissioning stage or treat it in only a cursory manner (Demuytere et al., 2025), while Environmental Impact Assessments (EIAs) rarely evaluate decommissioning impacts as distinct processes (Hall et al., 2020). Studies that have considered the ecological effects of partial removal provide important insights (Spielmann et al., 2023), but they have not connected these findings to broader life cycle environmental impacts and potential trade-offs. Likewise, the social dimension of OWF decommissioning remains largely unexplored, despite evidence from past offshore cases that public opinion can decisively influence outcomes. This study addresses these gaps by conducting a multi-criteria assessment of decommissioning options, applying LCA and a newly developed LCIA method for assessing local benthic biodiversity (Stranddorf et al., 2025b), and combining these environmental assessments with a national survey on public acceptance. Specifically, we evaluate 16 decommissioning scenarios for Horns Rev. 1, the first large-scale OWF built in the North Sea. Using LCA, we compare environmental impacts across scenarios and operationalize the LCIA method for marine biodiversity impacts in a real-world case study, demonstrating its potential to capture ecological consequences in LCA-based assessments of offshore wind infrastructure. In parallel, we examine public preferences based on a nationally representative survey conducted in Denmark. This is the first study to combine environmental life cycle impacts, marine biodiversity impacts, and public acceptance in a single assessment of OWF decommissioning. By linking environmental and social dimensions, the study contributes to a more holistic understanding of sustainable decommissioning strategies for offshore wind infrastructure.

2. Materials and methods

The OWF assessed in this study is Horns Rev. 1, which is located 14–20 km off the west coast of Jutland, Denmark, covering an area of 19.62 km^2 (European Commission, 2025). Horns Rev. 1 was commissioned by Elsam (later Dong, now Ørsted) in 2002 and is today co-owned by Ørsted and Vattenfall and operated by Vattenfall. This OWF was the world's first large-scale OWF and the first OWF in the North Sea. Whereas earlier wind farms had been constructed in more sheltered waters (e.g., Vindeby and Middelgrunden), Horns Rev. 1 showed the first case of construction in harsher open-sea conditions (Vattenfall, 2023). The farm consists of 80 turbines with a total capacity of 160 MW and is constructed on a sandy seabed (European Commission, 2025). The turbine foundations are constructed as steel monopiles with scour protection. The scour protection consists of aggregates like rocks and gravel, which are placed around the turbine foundation to prevent seabed erosion and maintain the foundation's integrity against currents and waves (Whitehouse et al., 2011). This study considers the wind farm itself, including the turbines and their foundations, the scour protection, and the infield cables. The offshore substation, the subsea export cables, and the electricity distribution network are not considered, as this is owned and operated by another company, and it wasn't possible to obtain data on it for this study.

2.1. Life cycle assessment

The LCAs of this study were conducted according to the International Reference Life Cycle Data System (ILCD) Handbook for LCA (European Commission, 2010) and the ISO standards for LCA (ISO, 2006a; ISO, 2006b). The guidelines define four stages of LCA practice: the goal and scope definition, the Life Cycle Inventory (LCI) analysis, the Life Cycle Impact Assessment (LCIA), and interpretation. The following sections present each LCA stage.

2.1.1. Goal and scope

In line with the objectives of the study, the goal of the LCAs was to determine the environmental impacts of the Horns Rev. 1 wind farm, considering different decommissioning scenarios. The considered lifetime of the OWF is 25 years, and the total net electricity production of the OWF during the 25-year period is estimated to be 11,990 GWh. The Functional Unit (FU), reflecting the primary function of the system

(Hauschild et al., 2018), was defined as "*1 kWh of electricity generated and delivered to the Danish electricity grid over 25 years*". Considering a yearly production of 480 GWh, the reference flow for this LCA, i.e., the number of OWFs required to accommodate the FU, is $8.34 \bullet 10^{-11}$.

The system boundaries (Fig. 1) applied in this study are cradle-to-grave, covering the raw materials production, manufacturing, installation, operation and maintenance, decommissioning, and material End-of-Life (EoL) phases of the OWF. The decision context of this LCA matches *Situation C (*European Commission, 2010*)*, as the results are descriptive and are not meant to be used directly for decision support. In line with the decision context, the LCI modelling framework followed an attributional approach, and the background system was modeled using average processes. Multifunctionality of processes was addressed by system expansion. An example of multifunctionality is the waste-treatment stage, which includes material recycling and recovery, thereby avoiding the production of the respective materials from virgin sources. Additionally, the waste treatment includes incineration of some materials, avoiding the production of electricity and heat from other sources. The avoided production was credited in this study, but the potential structural consequences this may have on other systems were out of the scope of this study.

16 decommissioning scenarios were defined for this study (Fig. 2), including variations in the amount of material left in situ when decommissioning. The scenarios were developed with inspiration from Spielmann et al. (2023) who investigated the marine biodiversity impacts of three scenarios: 1) leaving the scour protection in situ, and cutting the foundations 5 m above the seabed, 2) leaving the scour protection in situ, and cutting the structure 1 m below the seabed, and 3) removing the scour protection and cutting the structure 1 m below the seabed. The latter reflects the general decommissioning requirements, e. g., in Germany (Spielmann et al., 2023), whereas scenario 2 reflects decommissioning considerations from the United Kingdom (Britton, 2013; Drew, 2011). Scenario 1 has not been practiced in the North Sea and was merely considered an academic exercise by Spielmann et al. (2023).

We included more variations in our scenarios to identify where the largest impacts and savings are to be found. Additionally, we include the cables, which were not considered by Spielmann et al. (2023). The scenarios were designed to represent a broad and realistic range of technically feasible decommissioning options, inspired by current regulatory practices in Europe (e.g., Germany and the United Kingdom) and expanded based on engineering feasibility and expert judgment within the author team. The purpose was to avoid prematurely favoring specific scenarios and instead identify which components of decommissioning most influence overall environmental performance. The scenarios are named with a number (1, 2, 3, or 4), indicating how much of the monopile is removed, and a letter (A, B, C, or D), indicating how much of the cables and scour protection is removed. In scenarios starting with 1, the monopile is cut 5 m above seabed level; in scenarios starting with 2 the monopile is cut at seabed level; in scenarios starting with 3 the monopile is cut 2 m below the seabed level; and in scenarios starting with 4 the monopile is fully removed. In all scenarios including A (A1, A2, A3, and A4), the scour protection and cables are left; in all scenarios including B, the scour protection is left but only the cables that are buried below the scour protection are left; in all scenarios including C, the scour protection is left, but the cables are fully removed; and in all scenarios including D, both the scour protection and cables are fully removed.

2.1.2. *Inventory data collection*

Data was collected for all life cycle stages (Fig. 1). All foreground data was delivered by material experts and engineers at Vattenfall and from external suppliers. The foreground data is confidential and cannot be disclosed. However, an overview of the material composition of the entire wind farm and the proportion of the respective material included in the underwater structure is provided in Table 1 (indicated in weight percentage, wt%). The aggregates (scour protection) constitute the largest weight share of the wind farm (74 wt%), followed by steel (20 wt %). 45 wt% of the steel exists in the underwater structure, as does the largest proportion of the other metals (mainly in cables). All of the concrete and aggregates are placed under water, and 92 wt% of the plastics are also under water, as it makes up a large share of the underwater cables. The category "Other" primarily includes epoxy, mainly used for grout and corrosion protection. As no data exists regarding the energy use during decommissioning, it was conservatively assumed that full removal (Scenario 4D) requires twice as much energy as the construction phase. For the remaining scenarios, the energy use was scaled with the weight of materials removed.

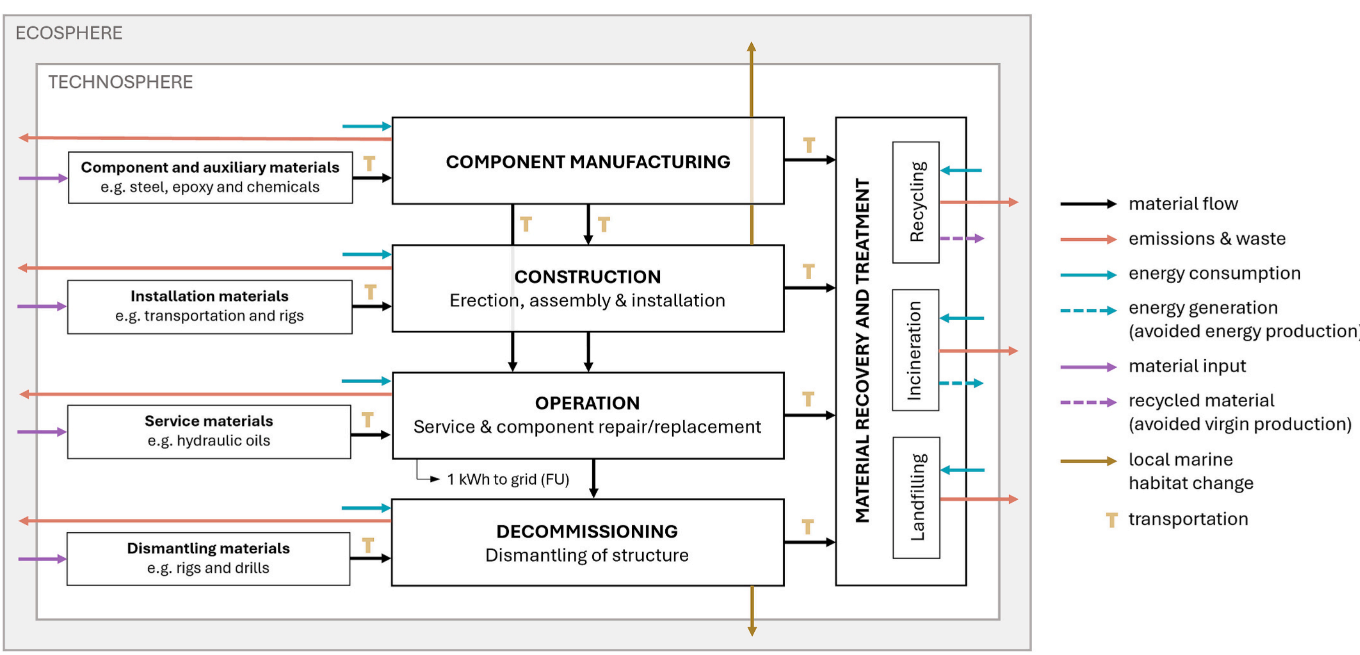

Fig. 1. System boundaries of the LCA conducted, covering cradle-to-grave of the Horns Rev. 1 wind farm, i.e., material extraction, manufacturing, installation, operating and maintenance, decommissioning, and End-of-Life (EoL). Illustration developed with inspiration from (Bonou et al., 2016).

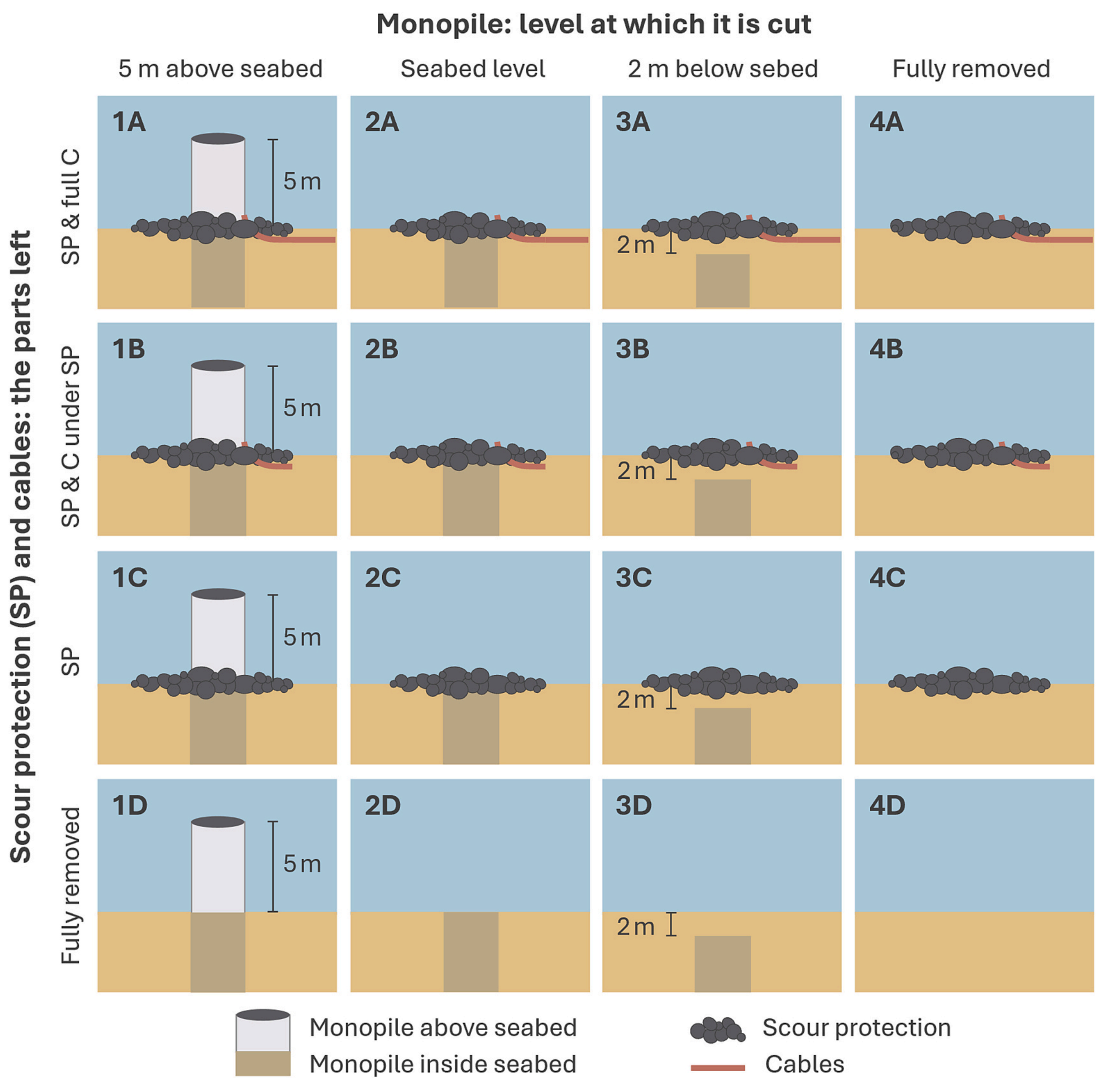

Fig. 2. The 16 decommissioning scenarios investigated in the case study. Each scenario is given a name consisting of a number (1–4) and a letter (A-B). The number indicates how much of the monopile is left when decommissioning, and the letter indicates how much of the scour protection and cables are left.

Table 1
Material composition of wind farm: the proportion (weight percentage: wt%) of each material compared to the total wind farm weight.

	Material proportion of total weight [wt%]	Proportion of material in underwater structure [wt%]
Steel	20	45
Aluminum	0,29	77
Copper	0,71	73
Other metals	1,4	100
Concrete	1,7	100
Aggregates	74	100
Composite	1,0	0
Plastics	0,54	92
Oil	0,093	0
Other	0,15	87

The material EoL phase includes treatment of waste, entailing either landfilling, incineration, or recycling of the materials removed from the sea (Table 2). Assumptions regarding the waste treatment method of each material are based on market practices and expert judgment documented in Vattenfall's Environmental Product Declaration (EPD) of electricity from Vattenfall's wind farms (Vattenfall, 2025). Assumptions regarding avoided production and substitution rates are based on Bonou

Table 2
Modelling assumptions regarding the End-of-Life (EoL) treatment of the Horns Rev. 1 wind farm materials. Assumptions regarding treatment method, avoided production and substitution rates are based on Bonou et al. (2016) and Vattenfall (2025).

	Proportion of the collected material [wt%]			
	Recycled	Incinerated	Landfilled	Avoided product and (substitution rate)
Aluminum	95		5	Average material in the market (90 wt%)
Other metals	90		10	
Aggregates	100			Virgin gravel (90 wt%)
Composite	70	30		Virgin sand, replacing sand in cement production (90 wt%); electricity and heat from incineration, average market product (100 wt%)
Concrete	100			Crushed gravel (90 wt%)
Oil	80	20		Oil recycling: lubrication oil (90 wt%)
Plastics		100		
Other		100		Incineration: Electricity and heat, average market product (100 wt%)

et al., 2016.

For the background system, including upstream and downstream processes not considered in the foreground system, background data were obtained from the databases GaBi Professional (Sphera) versions 2021.1, 2024.1, and 2024.2, and Ecoinvent versions 2.2 and 3.10. From Ecoinvent, the system model "Allocation, cut-off by classification" is applied. The general approach for database selection was to apply the data with the best temporal representation for each specific process. Sphera is mainly applied in the modelling of reinvestments, transportation, and waste treatment, and Ecoinvent covers most of the remaining processes. The general geographical data coverage is a European average (RER or Europe without Switzerland), but a global average (GLO) is applied for all transportation forms. Electricity is modeled to represent the mix in the country of consumption (generally Denmark/DK, but Norway/NO for aggregate extraction). Industry data was applied to cover a few processes, including the production of aluminum (EAA, 2005) and steel (IISI, 2005).

The impacts on local benthic marine biodiversity are investigated through a separate LCIA method (Stranddorf et al., 2025b), requiring specific inventory: information regarding the OWF age at the time of decommissioning (t), number of turbines (n_{tb}), footprint area per turbine structure (A_{tb}), the total area of the OWF (A_{OWF}), and the seabed type prior to installation. For Horns Rev. 1, the inventory information is: $t =$ 25 years, $n_{tb} = 80$ turbines, $A_{tb} = 491$ m^2 (diameter of circular footprint: 25 m), $A_{OWF} = 19.62$ km^2, and seabed before construction: sandy. The seabed between the turbines within the OWF is considered to be maintained as the seabed type on the site before construction.

2.1.3. Impact assessment

The LCAs were modeled in the LCA for Experts (Sphera) software, v10.9.0.31. The main LCIA method applied was the Environmental Footprint (EF) version 3.1 method, as recommended by the European Commission as part of the Product Environmental Footprint (PEF) method (European Commission, 2021). Impacts are reported on selected impact midpoint categories that correspond to those suggested by the Product Category Rules (PCR) for electricity generation (EPD International, 2024). The selected impact categories include climate change, ozone depletion, acidification, eutrophication, photochemical ozone formation, abiotic resource depletion (partially covered by EF 3.0), and water deprivation.

The marine biodiversity impacts were assessed separately using the method from Stranddorf et al. (2025b). The method assesses the local impacts on marine benthic biodiversity, defined here as organisms that live on, in, or close to the seabed as well as those inhabiting artificial hard substrates such as wind turbine foundations (adapted from Heery et al., 2017). The assessment is made by investigating changes in species richness from the habitat changes associated with wind farm construction and decommissioning, i.e., the change from a sandy seabed without OWF structures to a sandy seabed with OWF structures (construction), and the change from a sandy seabed with the OWF structures to the habitat left after decommissioning (various scenarios as illustrated in Fig. 2). The method also enables assessment of the lifetime impacts, i.e., comparing the species richness in the habitat left after decommissioning to the situation before construction (sandy seabed). It is worth noting that the assessed impacts from decommissioning cannot be directly compared to those associated with construction or the lifetime impacts, as they apply different reference states: the reference state for decommissioning impacts is the species richness on the structure just before decommissioning, whereas the reference state for construction and lifetime impacts is the richness in the seabed before construction.

The biodiversity data used in the method by Stranddorf et al. (2025b) originate from the "Biodiversity Information System of benthic species at ARtificial structures" (BISAR) dataset (Dannheim et al., 2025). The BISAR dataset includes observations from 17 artificial offshore structures (offshore wind farms, oil and gas platforms, and one research platform) and reference sites representing rock reefs and sandy seabeds. As the dataset does not include data from fully decommissioned OWFs, the temporal development of species richness over the 25-year operational lifetime was modeled using second-degree polynomial models, describing how species richness evolves from installation through operation to just before decommissioning. This modelling approach is further detailed in Stranddorf et al. (2025b). The model also accounts for differences in development patterns across taxonomic groups, thereby reflecting variation in species composition over time.

Benthic species exemplify the marine organisms most directly influenced by habitat changes from OWFs as the structures alter the habitat substrate, directly affecting the seabed communities (Desprez, 2000; Heery et al., 2017). The impacts on marine benthic biodiversity are expressed as Potentially Disappeared Fraction of species (PDF), integrated over the considered time aspect; thus, the final unit of marine biodiversity impacts is PDF.year, accounting for both positive and negative impacts, i.e., increases and decreases in species richness. It should be noted that the impacts attributed to construction are the integration of changes in species richness over the structure's lifetime (25 years), whereas the impacts attributed to decommissioning are only integrated over one year after decommissioning (Stranddorf et al., 2025b). The impacts are disaggregated for eight different taxonomic groups and alien species, which allows for a more detailed assessment, including considerations regarding changes in the species composition and habitat functionality. The eight taxonomic groups include *Chordata* (sea squirts, fish, lancelets & mammals), *Echinodermata* (starfish, brittle stars, sea urchins & sea cucumbers), *Bryozoa* (sea mats, horn wreck & lace corals), *Arthropoda* (crustaceans, marine insects & sea spiders), *Mollusca* (snails, slugs, mussels, oysters, cockles, clams & squid), *Annelida* (segmented worms), *Cnidaria* (Sea anemones, corals, sea firs & jellyfish), and *Porifera* (sponges). Alien species (as opposed to native species) are species that have spread or moved beyond the limits of their native geographic range into an area in which they do not naturally occur (Blackburn et al., 2014). In this study, alien species are species that do not naturally occur in the North Sea. They are not necessarily harmful (invasive) to their new ecosystem, but the prevention of alien species has been identified as the most effective way of minimizing the risk of invasion (Borgelt et al., 2024; Early et al., 2016). The occurrence of alien species is, therefore, included as an indicator of invasion risk.

2.1.4. Sensitivity and uncertainty analyses

The sensitivity of results from the EF 3.1 LCIA was investigated through four analyses: 1) by applying another LCIA method, the ReCiPe 2016 v1.1 Midpoint (H) method (Huijbregts et al., 2016), 2) by adjusting the content of the two heaviest materials (steel and scour protection aggregates) in the decommissioning inventory by ±10 wt%, 3) by adjusting the fraction of materials recycled by ±10 %pt., and 4) by adjusting the energy used in the decommissioning phase. We tested if the changes made in the four sensitivity analyses would change the conclusions of the study.

The uncertainty of the foreground LCI data was qualitatively assessed using the Pedigree Matrix approach (Chen and Lee, 2020; Weidema et al., 2013). This method evaluates each data point in the foreground system against five quality criteria: reliability, completeness, and temporal, geographical, and technological representativeness. Each criterion is scored on a scale from 1 (high data quality) to 5 (low data quality), and an overall Data Quality Rating (DQR) is calculated for each data point. The Pedigree Matrix approach was applied independently to support a structured assessment of data quality across scenarios and identify key data limitations, which should be considered when interpreting the results. Further details are provided in Supplementary Information (SI), Section 4.

2.2. Assessment of social acceptance

The social acceptance of OWF decommissioning was assessed using data from a survey conducted in the Danish society in the Autumn of

2023 as part of the Bifrost project (Prevost et al., 2022; Stranddorf et al., 2025a). To obtain a nationally representative sample, permission was granted by the Danish Health Data Authority to randomly select 60,000 individuals (aged 18–80 years) based on their personal identification numbers. The survey included several sub-surveys asking about the acceptance of different energy technologies. One of the sub-surveys concerned the decommissioning of offshore wind turbines and is used as input to this study. In total, 2348 completed the sub-survey about offshore wind decommissioning, resulting in an effective response rate of 11.74 %. As the survey included an information experiment, the respondents were divided into different groups depending on the information they were provided with. The information provided to the group considered in this study ($n = 230$ people) can be found in the SI Section 1, and additional details on the survey design in Stranddorf et al. (2025a). The provided information did not include details regarding the original biodiversity on the wind farm area, i.e., the biodiversity on the area before the wind farm was constructed. In this study, we focus on a single question (Fig. 3), asking the respondents to rate their preferred decommissioning option (A, B, C, and D) from the preferred option (1) to the least preferred option (4). The responses are analyzed descriptively, based on the distribution of rankings across the presented decommissioning options.

3. Results

3.1. Life cycle impacts

Across the environmental impact categories covered by the EF 3.1 LCIA method, Scenario 4C generally yields the lowest impacts, while Scenario 1 A yields the highest impacts among the considered 16 scenarios (see Fig. 4). This goes for all impact categories, except *Climate Change – Biogenic (CC-Biogenic)* and *Climate Change – Land Use and Land Use Change (CC-LULUC)* and *Eutrophication (EP) - Freshwater*. *CC-Biogenic* accounts exclusively for Greenhouse Gas (GHG) emissions of biogenic origin. The dominant source of impact in this category is electricity consumption associated with the treatment of metal scrap for recycling. The waste treatment processes for metals are highly electricity-intensive, and as the biomass combustion contribution embedded in the electricity mix is relatively large, the associated emissions are substantial. *CC-LULUC* primarily reflects GHG emissions arising from land transformation and occupation linked to transportation activities. Land transformation involves clearing vegetation for infrastructure such as roads and railways, which releases stored carbon. Land occupation impacts reflect the carbon fluxes of the respective land type, and as the carbon sequestration capacity of anthropogenic surfaces like roads and railways is very low (or equals 0), the occupation impacts are high. Additionally, upstream emissions related to the production of transport fuels and vehicle manufacturing, such as the extraction and refinement of oil and metals, also contribute significantly to this category. Impacts on *EP -Freshwater* are similarly

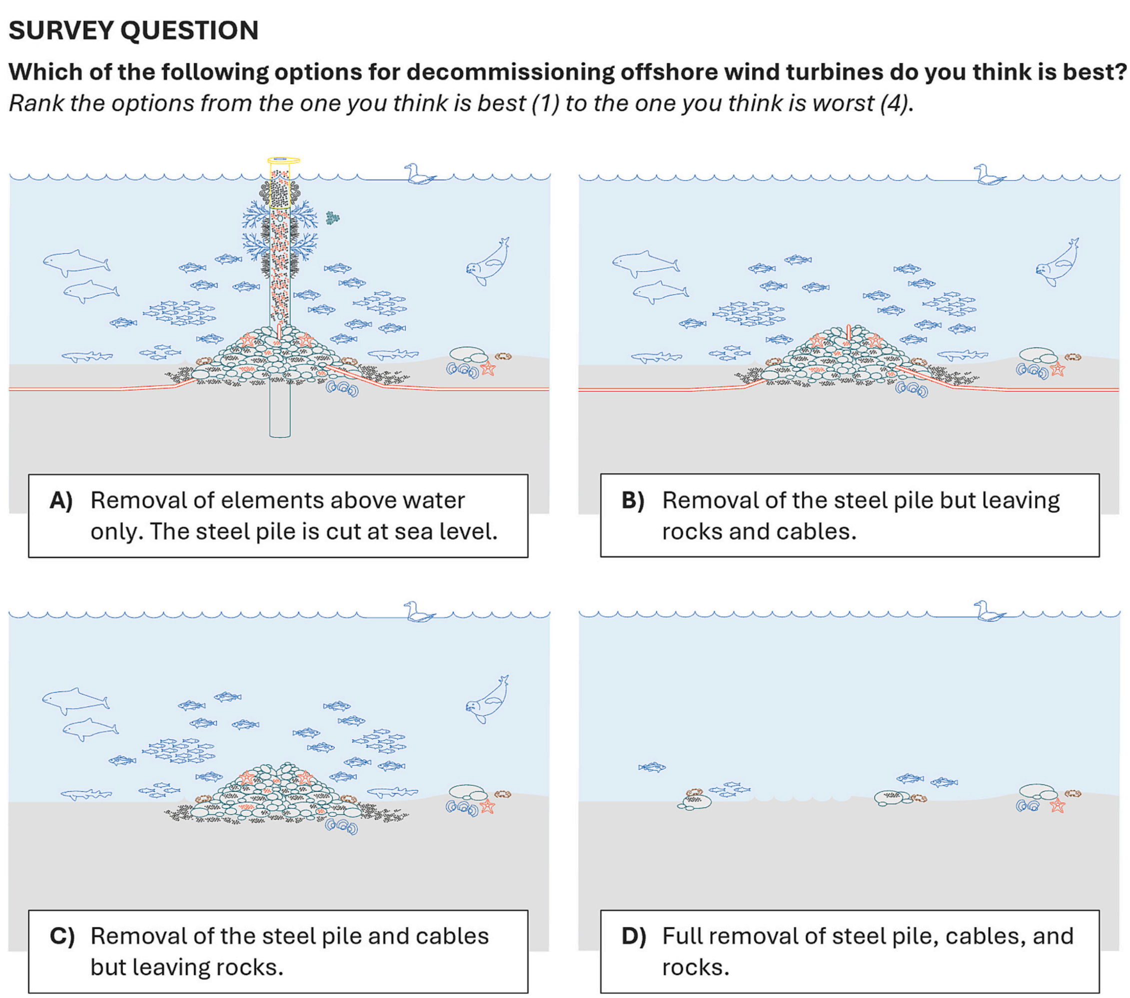

Fig. 3. Question asked to identify the preferred decommissioning option.

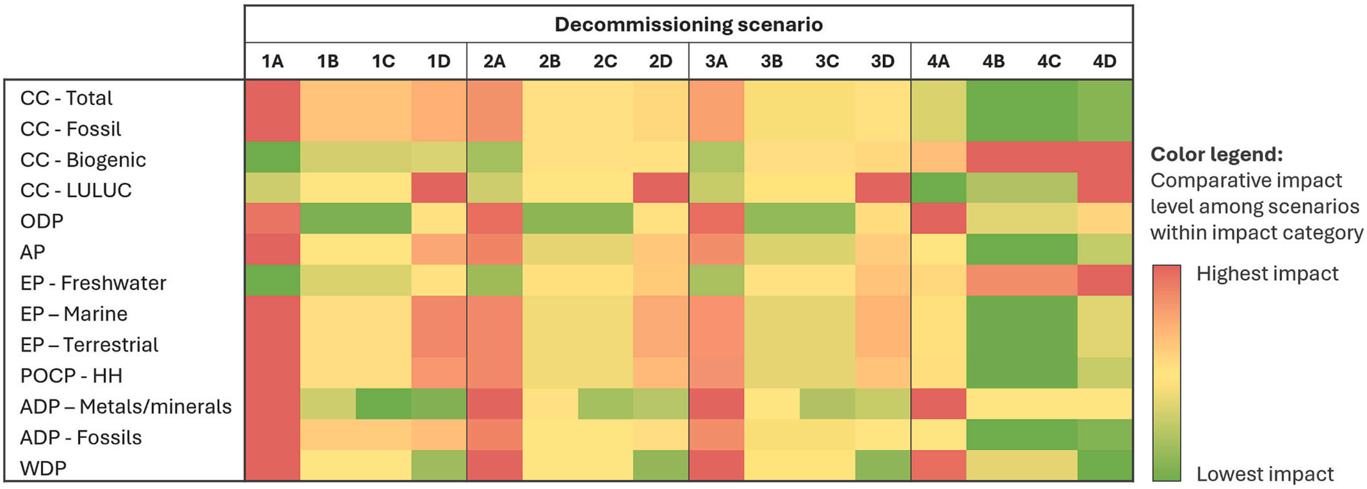

Fig. 4. Heat map of impacts per FU from each decommissioning scenario, considering the impact categories included in EF 3.1. The coloring reflects the relative performance among decommissioning scenarios within each impact category, varying from highest (red) to lowest (green). Abbreviations: CC (Climate Change), LULUC (Land Use and Land Use Change), ODP (Ozone Depletion), AP (Acidification Potential), EP (Eutrophication Potential), POCP-HH (Photochemical Ozone Formation Potential – Human Health), ADP (Abiotic Depletion Potential), and WDP (Water Deprivation Potential). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

driven by the treatment of metal scrap for recycling. This category captures nutrient emissions (nitrogen (N) and phosphorus (P), expressed as P equivalents) to freshwater bodies. Such emissions promote algal blooms, leading to oxygen depletion. Specifically, phosphorus-based detergents and acidic treatments used in metal cleaning processes generate nutrient-rich sludge that requires disposal, which contributes to the overall eutrophication potential.

When comparing scenarios within each number group (1, 2, 3, and 4), scenario C generally shows the lowest environmental impacts across the EF 3.1 categories. These scenarios involve the removal of the largest share of materials with high recycling potential, such as metals, while leaving the scour protection in place. The scour protection is characterized by a high mass and low recycling value, and its removal is associated with considerable energy use but only limited environmental benefit in terms of avoided primary production. Scenarios B and C within each number group (e.g., 1B and 1C, or 2B and 2C) exhibit nearly identical results across most impact categories. The key difference between these scenarios lies in the extent of cable removal. Cables contain valuable metals such as copper and aluminum, which are accounted for in the impact category *Abiotic resource Depletion Potential (ADP)* -

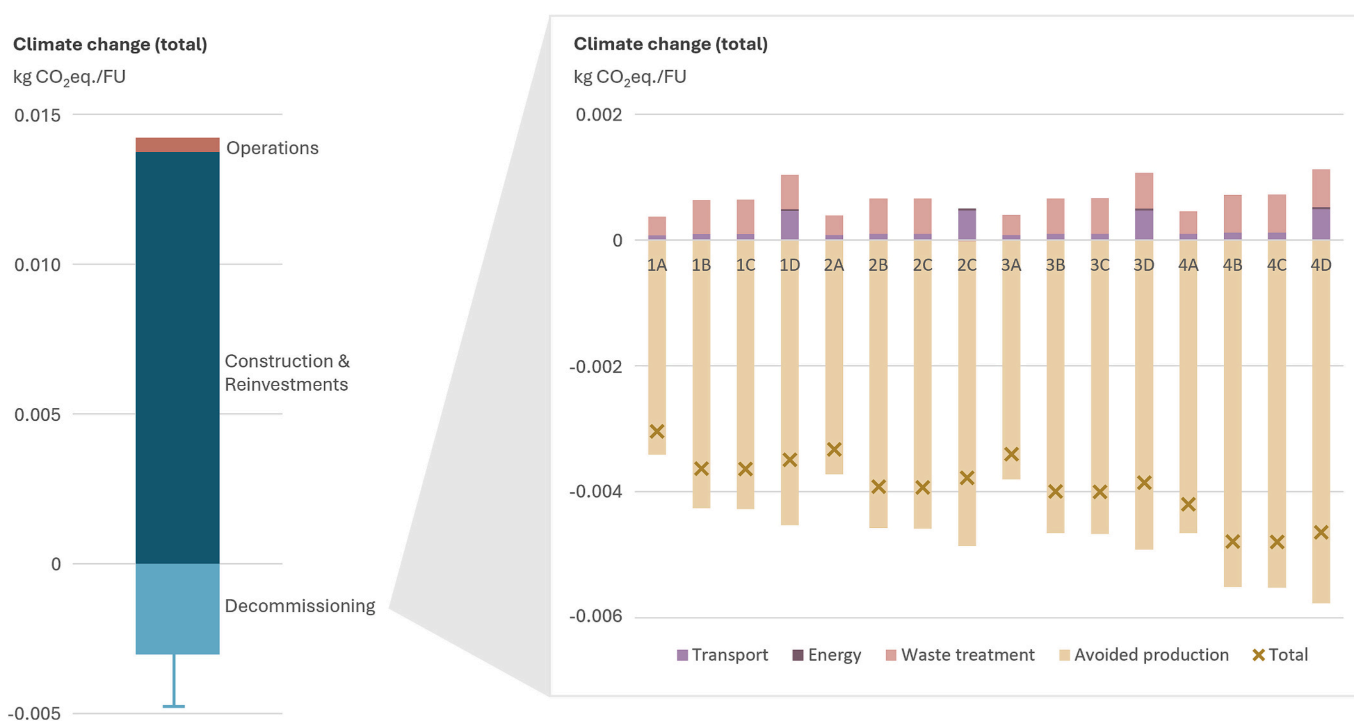

Fig. 5. Contribution to climate change (total). Left: contribution to climate change from each life cycle phase - construction and reinvestments (incl. Resource extraction, manufacturing of components, and construction process), operations, and decommissioning (a span). Right: The contribution to climate change from transportation, energy use, waste treatment, and avoided production, considering each decommissioning scenario. The X indicates the total impact on climate change from each scenario. Unit: kg CO_2 eq./FU.

minerals and metals. As a result, this is the only category in which a notable difference between scenarios 2 and 3 is observed.

The results of the sensitivity analyses can be found in SI, Section 3, which confirms the robustness of the findings from the main analysis. The applied variations in key parameters, including the steel or aggregate content, recycling rates, energy use, and the applied LCIA method, do not alter the overall conclusions regarding the scenario performances. The Pedigree Matrix analysis of foreground LCI data identified generally high data quality for construction-related processes, while higher uncertainty was associated with several decommissioning and waste treatment processes. This increased uncertainty primarily relates to unknowns regarding the quantities of materials to be removed and the realistic shares of materials that will be recycled, landfilled, and incinerated at the EoL. The reliability of inventory data for earlier life cycle stages is generally higher, as decommissioning activities have not yet been carried out, in contrast to construction and maintenance. These data quality insights should be considered when interpreting the results, particularly in the comparison of decommissioning impacts to construction and operational impacts. The Pedigree Matrix is to be found in SI, Section 4.

Focusing on the total impacts on climate change (CC-Total) (Fig. 5), the decommissioning phase results in net negative emissions across all scenarios. This outcome is due to the environmental credits associated with the avoided production of virgin materials and energy, such as electricity and heat, enabled by the recycling or recovery of decommissioned components. The net impacts from the decommissioning phase range from −0.0030 kg CO_2-eq per functional unit (FU) in Scenario 1 A to −0.0048 kg CO_2-eq/FU in Scenario 4C. These contributions correspond to reductions equivalent to 21–34 % of the combined emissions from the construction, reinvestment, and operational phases, underscoring the significant climate benefits that can be achieved through material recycling and recovery in the end-of-life management.

The largest positive impacts come from the waste treatment processes (incineration, landfilling, and recycling treatment), from which the incineration of plastics and the treatment of metals for recycling contribute the most to the climate change impacts of decommissioning. Additionally, in scenarios where scour protection is removed (1D, 2D, 3D, and 4D), transport-related emissions emerge as a prominent source of impact. This is attributed to the high mass of aggregate materials and the associated fuel demands for transportation, primarily in the form of

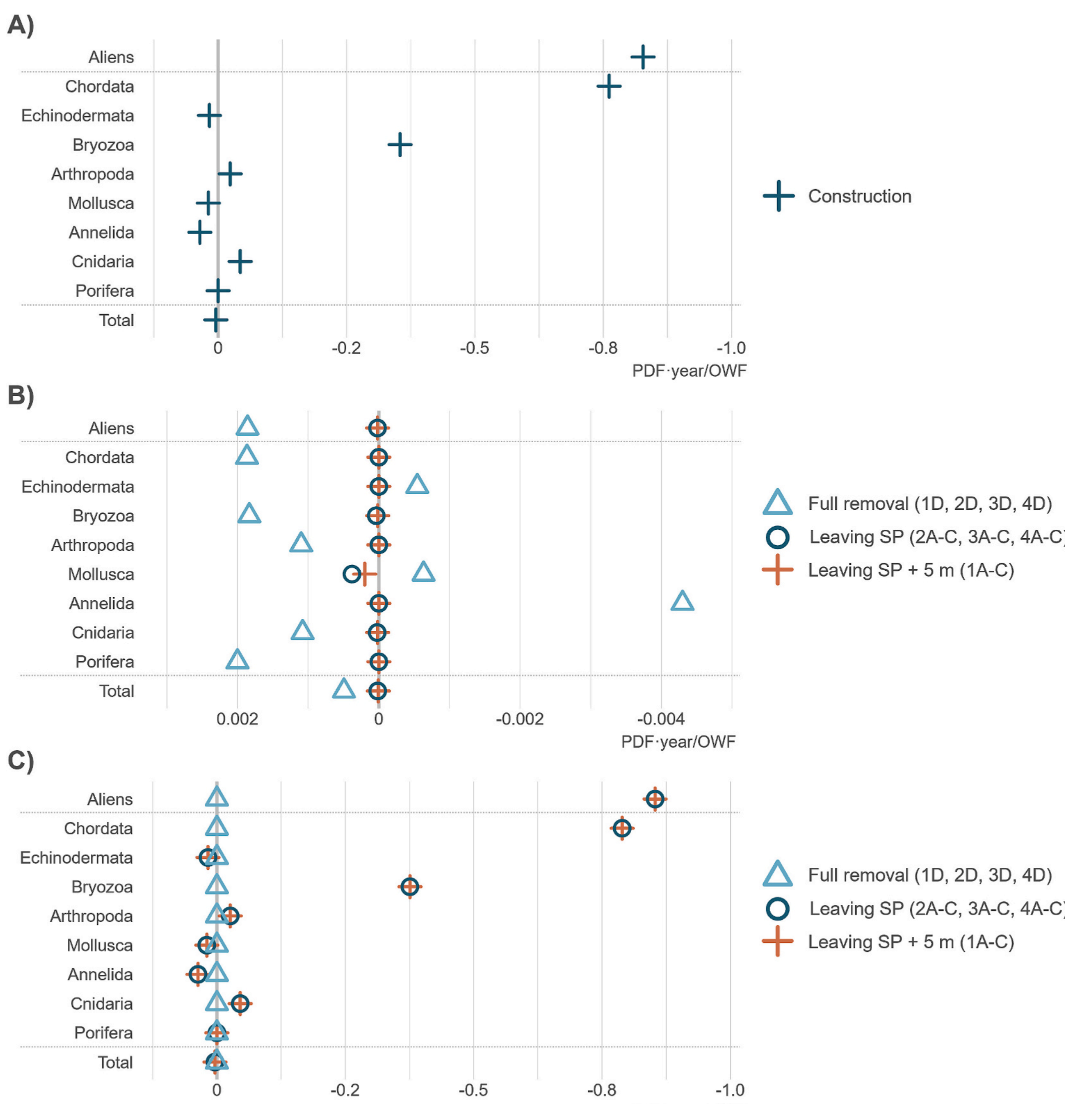

Fig. 6. Impacts on local marine benthic biodiversity from construction (A), decommissioning considering each scenario (B), and from the whole wind farm lifetime, considering each decommissioning scenario (C). The impacts are shown for all species (Total) and disaggregated into eight taxonomic groups and alien species. Alien species should be evaluated apart from other species. Be aware that the increases in richness are to the right and decreases to the left on the x-axis. The unit PDF.year/OWF: Potentially Disappeared Fraction of species (PDF) over time (year) per Offshore Wind Farm (OWF). Other abbreviations: SP (Scour Protection).

diesel combustion. Consequently, while the removal of scour protection may provide minimal material recovery benefits, it substantially increases the fuel-related emissions burden.

3.2. Marine biodiversity impacts

When interpreting the assessed impacts on local benthic biodiversity (Fig. 6), negative values indicate net gains in species richness, while positive values indicate species losses. It is important to note that the reference states applied in the impact modelling differ between the life cycle stages: both construction and lifetime impacts are assessed relative to the pre-construction baseline (i.e., the sandy seabed before construction), whereas decommissioning impacts are assessed in relation to the species richness found on the structure prior to its removal. Consequently, the marine biodiversity impacts of decommissioning cannot be directly compared to those from construction or the full lifetime. Additionally, it should be noted that the impacts attributed to construction reflect the habitat change caused by construction and the subsequent operational phase: that is, they integrate the changes in PDF from the time of construction to decommissioning, using the pre-construction seabed richness as a reference.

The total species richness within the wind farm area remains nearly unchanged in the operational phase, compared to the pre-construction seabed richness, with only a slight overall decline. This small reduction is mainly driven by decreased habitat availability for *Annelida* (segmented worms), which are particularly abundant in sandy seabed types (Ager, 2005) and are partially displaced by the introduction of turbine foundations' hard substrates. It should be noted that this effect is highly local, confined to the immediate footprint of the foundations; at the scale of the entire wind farm or regional seabed, *Annelida* and other soft-sediment species, remain largely unaffected. However, substantial local shifts in species composition are observed. Notably, there are pronounced increases in the richness of *Chordata* (sea squirts, fish & lancelets) and *Bryozoa* (sea mats, horn wrecks & lace corals), reflecting the colonization potential of the artificial hard surfaces introduced by the wind turbine foundations. Conversely, reductions are observed in *Annelida*, *Mollusca* (snails, slugs, mussels, oysters, cockles, clams & squid), and *Echinodermata* (star-fish, brittle stars, sea urchins & sea cucumbers).

In the decommissioning scenarios involving full removal of the structural parts above the seabed (1D, 2D, 3D, and 4D), similar shifts in species composition occur - albeit in the opposite direction. The removal of hard substrates allows species typical of sandy seabeds (e.g., *Annelida*) to recolonize the local area of the former foundations, leading to a resurgence in their richness. In contrast, species groups such as *Chordata*, which preferentially colonize hard surfaces, show reduced richness post-decommissioning, as the habitat returns to a sandy seabed state. The decommissioning scenarios in which the scour protection (SP), or the scour protection plus a 5 m segment of the vertical steel structure (SP + 5 m), are left in place show minimal impacts on overall benthic biodiversity. This indicates that the scour protection serves as a habitat for most species found on the turbine structure, including those located on the upper parts of the foundation. A notable exception is *Mollusca*, which are predominantly found on the upper steel sections and thus decline when only the scour protection is retained.

The lifetime marine biodiversity impacts are assessed by comparing the post-decommissioning state to the pre-construction baseline. In the case of full removal at decommissioning, where the seabed is returned to its original sandy state, lifetime impacts are effectively zero across all taxonomic groups. For the scenarios where the scour protection or scour protection +5 m of the vertical structure is left in place when decommissioning, yield biodiversity outcomes comparable to those observed during the construction phase: a strong increase in species richness for *Chordata* and *Bryozoa*, and more modest changes for other groups. While total species richness remains close to unchanged in these cases, the most significant ecological effect is a shift in species composition, indicating a change in habitat functionality rather than a net loss or gain in biodiversity.

In LCA, an increase in species is typically considered positive. However, unlike other species, an increase in alien species cannot be considered positive, as they may pose a risk to the native species and the ecosystem's functionality. Consequently, alien species should be evaluated apart from other taxa. As the wind farm structures host more alien species than the reference sandy seabed, we see an increase in alien species from the construction and lifetime impacts, except when removing everything at the point of decommissioning. Looking separately at the decommissioning impacts, comparing the post-decommissioning state to the pre-decommissioning structure, fully removing the structure will result in a large decrease in alien species, while leaving the SP or SP + 5 m will maintain a large share of the aliens.

3.3. Social acceptance of decommissioning scenarios

In the survey assessment, the respondents were asked to rank the four decommissioning scenarios from most to least preferred (priority 1 to 4). A chi-square test shows that the distribution of responses within each priority level is significantly different from a uniform distribution at a 5 % significance level (see SI, Section 1). Scenario D, representing full removal of all components, emerged as the most preferred option, with 63 % of respondents ranking it as their first priority (Fig. 7). The second most preferred option (rated first by 19 % of respondents) was scenario A, which lies at the opposite end of the decommissioning spectrum, compared to scenario D. In this scenario, all sub-sea elements are left in-situ while only above-water structures are removed. Scenarios B and C represent intermediate options, both retaining the scour protection but differing in the treatment of cables: scenario B leaves the cables in place, while scenario C includes their removal. Although the two scenarios are similar in terms of the illustrated biodiversity attraction, scenario C received approximately twice as many first-priority votes (12 %) as scenario B (6 %). Despite being the clear first choice for a majority, scenario D received almost no second- or third-priority rankings, indicating a polarized perception: respondents either strongly favored full removal or placed it at the bottom of their preference list. In contrast, scenarios B and C dominated the second-priority rankings, together accounting for 90 % of those votes. Third-priority rankings were more evenly distributed across scenarios A, B, and C. Fourth-priority rankings were mainly assigned to scenarios A and D,

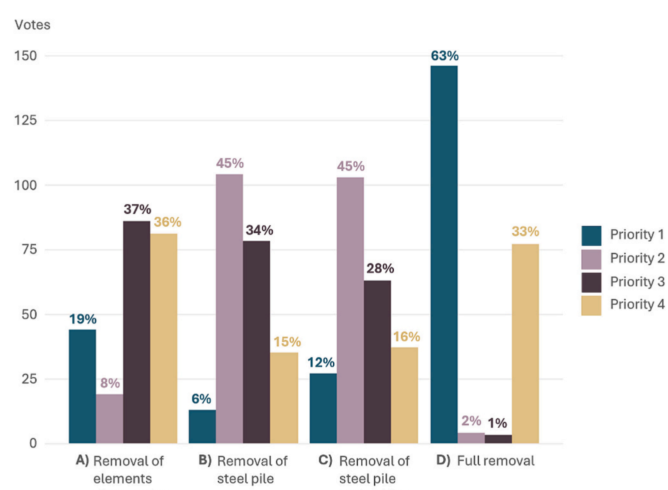

Fig. 7. Responses to the survey question regarding the preferred option for decommissioning ($n = 230$). The respondents were asked to rank the options from the one they prefer the most (Priority 1) to the one they prefer the least (Priority 4). Percentages indicate the response rate within each priority category.

though the distribution was more diffuse compared to priority 1 responses.

As part of a supplementary analysis, we examined whether the ranking of decommissioning scenarios varied according to gender, age group, educational attainment, and household income using Chi-square tests. The results indicate that male and female respondents generally agree on the scenario rankings, particularly with respect to scenarios A and D. The Chi-square test revealed no statistically significant differences in rankings between genders. However, age appears to influence preferences. Respondents aged 20–40 years were significantly more favorable toward scenario A compared to scenario D, relative to those aged 41–60 and 61–80 years ($p < 0.05$). When comparing rankings across educational levels—categorized as elementary/high school, vocational training/bachelor's degree, and master's/PhD - no significant differences were observed. Similarly, no significant variation in scenario rankings was found across household income groups. In summary, age was the only demographic factor associated with significant differences in scenario preferences, with younger respondents showing a stronger preference for scenario A over scenario D. Detailed ranking distributions and Chi-square tests across demographic groups are presented in SI, section 1.3.

4. Discussion

4.1. *Interpreting benthic biodiversity impacts: Reference states and habitat functionality*

Assessing impacts on marine benthic biodiversity presents a number of interpretation challenges, particularly when the construction or decommissioning intervention alters the fundamental characteristics of the habitat. In the case of OWF structures, the transition between sandy substrate habitats and hard substrate habitats (e.g., rock-based scour protection or steel foundations) represents a key driver of biodiversity change. In such cases, increases or decreases in species richness reflect not only the loss or gain of species but also a shift in species composition and, consequently, in habitat functionality. While the current assessment considers only species richness (or diversity), it does not capture changes in ecosystem functionality resulting from shifts in species composition. These functional changes may influence ecosystem services and are an important aspect for future methodological development in LCIA methodology.

One of the central interpretive challenges is the selection of the reference state against which impacts are assessed. In this study, the construction and lifetime impacts were evaluated against the sandy seabed present at the site before installation, while the decommissioning impacts were assessed relative to the species present on the structures at the end of their operational life. These reference choices strongly influence the results and their interpretation. The sandy seabed reference is ecologically relevant for restoration considerations, yet it may not reflect a truly "pristine" baseline, given the historical and ongoing anthropogenic disturbances in the North Sea, particularly from bottom trawling and infrastructure development (Callaway et al., 2007; Desprez, 2000). These pressures have reduced the occurrence of natural hard substrates, making the artificial structures introduced by OWFs functionally unique habitats in the regional seascape. This raises an important ecological question: Should the preferred post-decommissioning state aim to restore the pre-construction sandy seabed, or should it maintain the emergent reef-like habitat that the structures have created? The answer is not straightforward. If the management goal is to support sandy-bottom specialists or restore pre-development conditions, then removal of the structures, including the scour protection, may be preferable. However, if the goal is to enhance habitat heterogeneity in an otherwise homogenized marine environment, maintaining hard substrates may be beneficial.

An additional complexity arises from the role of artificial structures in supporting alien species. While the presence of hard substrates increases total species richness, it also fosters conditions favorable to non-native (alien) species. The marine biodiversity assessment indicated a notable increase in alien species associated with the wind turbine structures. Many of these non-indigenous species may already be present elsewhere in the wider region on other artificial or coastal structures (e.g., buoys or harbor walls). Therefore, their colonization of offshore wind turbines represents a local addition, regardless of their regional presence.

Although species richness is often used as a proxy for biodiversity value, not all species are equal in ecological function or conservation priority. In particular, the distinction between non-native and invasive alien species is critical. The presence of the former may not necessarily constitute a negative outcome unless they pose a dominant threat to native biodiversity or ecosystem functioning. As such, future research should seek to identify not only species richness but also the presence of alien species with invasive traits, as well as their functional traits. Additionally, the assessment of marine benthic biodiversity impacts in this study focuses solely on local species disappearance, i.e., species that may no longer be present at the site due to habitat alterations. It does not reflect global extinction. To enhance the ecological relevance and comprehensiveness of such assessments, future research should aim to expand the methodology to also account for global biodiversity impacts, including the broader conservation status and distribution of affected species. In addition, future work should distinguish marine biodiversity changes caused by OWFs from those driven by other pressures such as climate change, which may also influence species composition through range shifts (Cheung et al., 2009). This distinction would improve the attribution of observed biodiversity changes to specific drivers.

4.2. *Public preferences of decommissioning scenarios*

The survey results reveal a clear preference for full removal (survey Scenario D) but considerable diversity in the ranking of less-preferred options. The strong support for full removal, selected as the top priority by 63 % of respondents, suggests a widespread desire to restore the marine environment to its original state, potentially reflecting concerns about human influence on the seabed, long-term underwater structures, or a strong climate/resource responsibility ethic. Among those prioritizing Scenario D, there is a clear pattern in the subsequent rankings, with most selecting Scenario C as their second choice and Scenario A as their least preferred option (see SI, Section 1). This suggests a consistent logic among this group: the less left behind, the better.

At the other end of the spectrum, Scenario A was also selected as a first priority by a notable share (19 %), indicating that some respondents value minimal intervention or potentially see ecological or structural value in leaving parts of the installation in place. Interestingly, Scenarios B and C, which are ecologically similar in their illustrated biodiversity outcomes, received notably different levels of support on the first priority. Scenario C, which involves the removal of cables, received twice as many first-priority votes as B, likely reflecting broader public concerns around resource recovery, seabed pollution, or potential long-term risks. The distribution of lower-ranked priorities was more fragmented, suggesting that when a scenario was not a respondent's first choice, their evaluation was driven by varying rationales, such as material recycling, visual disturbance, or general environmental concern.

It is important to acknowledge that the respondents were presented with simplified, literature-based scenarios rather than results grounded in detailed environmental assessments. The illustrations accompanying these scenarios included depictions of biodiversity on and around the turbine foundations, which may have influenced respondents' perceptions. However, a study by Stranddorf et al. (2025a) found that the level of biodiversity shown in such illustrations did not significantly affect responses. Had the information provided and the question been phrased differently, preferences may have differed. Moreover, aligning the scenarios more closely with those assessed in the LCA, such as partial removal configurations or more nuanced cut-depth options, could yield more precise insights. Nonetheless, the findings underscore the critical role of stakeholder perceptions in shaping socially acceptable decommissioning strategies and highlight the importance of transparent communication around trade-offs in environmental, ecological, and technical dimensions.

4.3. Balancing environmental impacts and public preferences

This study highlights the multifaceted trade-offs involved in the decommissioning of OWFs, with Scenario 4C (leaving only scour protection) emerging as the preferred option from a life cycle environmental impact perspective, Scenario D of the survey (full removal) as the most socially accepted, and no universally optimal solution evident from the biodiversity assessment.

From the LCA using the EF 3.1 LCIA method, Scenario 4C yielded the lowest impacts across the majority of environmental categories. Scenario 4C is characterized by the removal of most components with high recycling value while leaving the scour protection in place. Thus, the results suggest that the removal of metals and other high-value materials provides significant benefits through avoided production, while the removal of scour protection contributes disproportionately to impacts, primarily due to its low recycling value, high mass, and the associated fuel-intensive transport required. Therefore, from an LCA standpoint, optimal environmental performance is achieved by maximizing recycling benefits while avoiding unnecessary removal of materials with low recycling value and high environmental impacts. In contrast, the social acceptance survey revealed a clear preference for full removal of all components, including scour protection. This preference may be driven by a desire for restoration of the original seabed or a precautionary position toward leaving man-made structures in the marine environment. However, the polarized distribution of responses, with survey Scenario D receiving both the highest proportion of first-priority rankings and a significant share of fourth-priority rankings, underscores the complexity and diversity of public attitudes toward decommissioning. The assessment of impacts on local marine benthic biodiversity did not point to a single most beneficial scenario. As previously discussed, the preferred decommissioning strategy depends on the ecological reference state and the goal for the site. If restoration to the original sandy habitat is prioritized, full removal is preferable. Conversely, if habitat diversification and support for hard-substrate species are desired, leaving scour protection in place can be justified. However, this also sustains the presence of alien species, whose long-term ecological effects remain uncertain.

Taken together, Scenario 4C offers a compelling compromise. While it does not fully satisfy the prevailing public preference for full removal, it significantly reduces life cycle environmental impacts and may offer some biodiversity benefits if hard-substrate-associated species are prioritized. Nevertheless, the increase in alien species under this scenario signals a potential ecological risk that requires further consideration. The findings underscore the importance of a multi-criteria approach to decommissioning, including general impact categories of LCA, local marine biodiversity impacts, and social acceptance. Scenario-specific trade-offs highlight that decision-making cannot rely solely on any single dimension but should be informed by a holistic understanding of environmental and social priorities.

It should also be noted that the climate change assessment conducted in this study does not include changes in organic carbon storage in the seabed. Recent research indicates that the deposition of organic carbon in the seabed soil may increase within and around OWFs during their operational lifetime (De Borger et al., 2021), with local accumulations of up to ~10 %. Depending on the decommissioning scenario, larger or smaller parts of this carbon may be released during decommissioning due to seabed disturbance. These processes are currently not represented in LCIA models but could influence the overall greenhouse gas balance of OWFs and should be considered in future methodological developments. Noteworthy, a greater impact than decommissioning can come from trawling if that is allowed in the OWF area during its lifetime, which is an activity not included in the LCA looking at the OWF impacts.

4.4. Transferability of findings

While this study presented a multi-dimensional assessment of OWF decommissioning, the findings cannot be directly applied to other wind farms. The LCA results reflect the specific material composition, size, and operational profile of Horns Rev. 1. Because wind farm designs and material use vary across projects and generations, LCAs should be developed for each individual project using site-specific inventory data. Moreover, as end-of-life technologies and recycling practices evolve, so will the relative environmental impacts of different decommissioning strategies. For example, a shift toward electric transport could lower emissions from scenarios requiring heavy material transport, such as scour protection removal. Additionally, the applied LCIA method for assessing marine benthic biodiversity impacts is tailored to the North Sea context, relying on regional ecological data. Its use outside this region would require re-parameterization to reflect different seabed types, habitat dynamics, and species assemblages. Even within the North Sea, biodiversity outcomes will vary depending on factors such as seabed type, wind farm size, and structure age.

The social acceptance component, while not directly linked to Horns Rev. 1, was based on a nationally representative Danish survey. As such, the findings reflect public attitudes within a specific cultural and policy context. Public perceptions of decommissioning strategies may differ substantially in other countries, depending on local values, knowledge, governance structures, and experience with offshore infrastructure.

Despite these limitations, this study serves as a first attempt to integrate environmental life cycle impacts, local marine biodiversity effects, and social preferences into a unified assessment framework for OWF decommissioning. The approach demonstrates the value of considering multiple dimensions of sustainability and stakeholder interest when evaluating decommissioning strategies. Future applications of this framework can support more context-sensitive planning by adapting the individual components to local ecological, technical, and social conditions.

4.5. Policy implications

The findings of this study provide several implications for policy and regulatory decision-making. Partial removal strategies, such as those that retain scour protection, can offer strong environmental performance and, under certain conditions, enhance local biodiversity by preserving habitat heterogeneity. However, the ecological outcomes of such strategies are highly context dependent. For example, in areas where natural hard substrates are already present and degraded (e.g., gravel beds, oyster reefs), artificial hard substrates may support restoration of these ecosystems. Conversely, in sandy environments, retaining hard substrates may alter local microbial communities and associated ecological functions. While public preferences in our case study favored full removal, this may reflect limited awareness of environmental trade-offs. Transparent communication of ecological and climate-related impacts could help build support for more balanced strategies.

To accommodate emerging evidence and diverse stakeholder values, regulatory frameworks should allow for flexibility in decommissioning approaches rather than prescribing full removal as the default. Instead, decisions should be made case-by-case, and consider general environmental performance, including biodiversity, and public acceptability. Additionally, decommissioning should ideally be considered already in the wind farm design phase, particularly if the intention is to retain scour protection as a nature restoration measure. In this context, early and inclusive stakeholder engagement becomes essential for securing social license to operate and ensuring robust, ecologically sound, and publicly legitimate outcomes. This study supports a more adaptive and participatory approach to decommissioning policy, where environmental science, technical feasibility, and social values are brought into alignment.

5. Conclusion

This study offers a novel, multi-dimensional assessment of OWF decommissioning by integrating life cycle environmental impacts, including local benthic marine biodiversity outcomes, and public preferences. Applying this approach to Horns Rev. 1 – the oldest large-scale OWF in the North Sea - reveals that no single decommissioning option is universally optimal across all of the assessed environmental and social dimensions.

From an environmental LCA perspective, Scenario 4C, in which all materials with high recycling value are removed while scour protection stones are left in place, performs best across most impact categories. This reflects the benefits of recycling high-value materials while avoiding the intensive energy use associated with removing low-value, heavy components. In terms of biodiversity, the preferred scenario depends on the ecological goal: full removal restores the original sandy seabed and reduces the presence of alien species, while partial removal maintains reef-like structures that support more diverse, though sometimes non-native, species communities. Public preference, as measured in a national Danish survey, clearly favors full removal, likely driven by a desire for environmental restoration or caution toward artificial seabed structures.

Balancing these perspectives, Scenario 4C represents a pragmatic and environmentally responsible compromise, offering strong performance in terms of life cycle impacts, including local marine benthic biodiversity impacts, and partial alignment with societal expectations - particularly among respondents who prioritize material recovery and minimal seabed intervention. While not the top-ranked option in the public survey, 4C aligns with the second-choice ranking for many respondents and avoids the most polarized responses seen for full removal.

Based on these findings, we recommend that regulatory frameworks and project developers consider partial removal strategies that optimize environmental performance and biodiversity outcomes while engaging public stakeholders early in the planning process. Transparent communication about environmental trade-offs and site-specific ecological goals will be essential to secure social license and ensure ecologically sound decommissioning outcomes. Future studies should aim to further refine biodiversity impact methods and explore how informed public dialogue may shift preferences when presented with quantified environmental data.

CRediT authorship contribution statement

Liv Stranddorf: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft. **Jacob Ladenburg:** Conceptualization, Funding acquisition, Methodology, Validation, Supervision, Writing – review & editing. **Agnes Rönnblom:** Data curation, Methodology, Software, Validation, Writing – review & editing. **Lena Landström:** Data curation, Validation, Supervision, Writing – review & editing. **Stig Irving Olsen:** Conceptualization, Funding acquisition, Methodology, Validation, Supervision, Writing – review & editing.

Declaration of competing interest

Liv Stranddorf reports financial support was provided by Innovation Fund Denmark (grant number 1044-00104B) and Biowins, a Vattenfall research support fund. Jacob Ladenburg reports financial support was provided by Danish Energy Technology Development and Demonstration Programme (project number 74021–9007). Given their role as editorial board member, Stig Irving Olsen had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to another journal editor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary Information

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.108253.

Data availability

Some supporting data is reported in the supplementary information, consisting of one file. Foreground data used for the Life Cycle Assessment is confidential to Vattenfall and associated providers of wind farm components, and cannot be disclosed. Survey responses used for assessing public preferences are confidential and cannot be disclosed.

References

Adedipe, T., Shafiee, M., 2021. An economic assessment framework for decommissioning of offshore wind farms using a cost breakdown structure. Int. J. Life Cycle Assess. 26 (2), 344–370. https://doi.org/10.1007/s11367-020-01793-x.

Ager, O., 2005. *Spiophanes bombyx*: A Bristleworm. Marine Biological Association of the United Kingdom, Plymouth. Retrieved August 2 from. https://www.marlin.ac.uk/species/detail/1705.

Bate, R., 1995. Lessons from the Brent spar. Econ. Aff. 16 (1), 39. https://doi.org/10.1111/j.1468-0270.1995.tb00513.x.

Blackburn, T.M., Essl, F., Evans, T., Hulme, P.E., Jeschke, J.M., Kuhn, I., Kumschick, S., Markova, Z., Mrugala, A., Nentwig, W., Pergl, J., Pysek, P., Rabitsch, W., Ricciardi, A., Richardson, D.M., Sendek, A., Vila, M., Wilson, J.R., Winter, M., Bacher, S., 2014. A unified classification of alien species based on the magnitude of their environmental impacts. PLoS Biol. 12 (5), e1001850. https://doi.org/10.1371/journal.pbio.1001850.

Bonou, A., Laurent, A., Olsen, S.I., 2016. Life cycle assessment of onshore and offshore wind energy-from theory to application. Appl. Energy 180, 327–337. https://doi.org/10.1016/j.apenergy.2016.07.058.

Borgelt, J., Dorber, M., Geron, C., Kuipers, K.J.J., Huijbregts, M.A.J., Verones, F., 2024. What is the impact of accidentally transporting terrestrial alien species? A new life cycle impact assessment model. Environ. Sci. Technol. 58 (7), 3423–3436. https://doi.org/10.1021/acs.est.3c08500.

Britton, M., 2013. Decommissioning Programme for London Array.

Callaway, R., Engelhard, G.H., Dann, J., Cotter, J., Rumohr, H., 2007. A century of North Sea epibenthos and trawling: comparison between 1902-1912, 1982-1985 and 2000. Mar. Ecol. Prog. Ser. 346, 27–43. https://doi.org/10.3354/meps07038.

Chen, X., Lee, J., 2020. *The Identification and Selection of Good Quality Data Using Pedigree Matrix* Sustainable Design and Manufacturing 2020, Singapore.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Pauly, D., 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish Fish. 10, 235–251. https://doi.org/10.1111/j.1467-2979.2008.00315.x.

Dannheim, J., Kloss, P., Vanaverbeke, J., Mavraki, N., Zupan, M., Spielmann, V., Degraer, S., Birchenough, S.N.R., Janas, U., Sheehan, E., Teschke, K., Gill, A.B., Hutchison, Z., Carey, D.A., Rasser, M., Buyse, J., van der Weide, B., Bittner, O., Causon, P., Krone, R., Faasse, M., Wrede, A., Coolen, J.W.P., 2025. Biodiversity Information of benthic Species at ARtificial structures - BISAR. Sci Data 12 (1), 604. https://doi.org/10.1038/s41597–025-04920-1.

De Borger, E., Ivanov, E., Capet, A., Braeckman, U., Vanaverbeke, J., Grégoire, M., Soetaert, K., 2021. Offshore windfarm footprint of sediment organic matter mineralization processes. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.632243.

De Luca Peña, L.V., Bas, B., Dewulf, J., van den Burg, S.W.K., Taelman, S.E., 2024. Environmental life cycle assessment of multi-use of marine space: a comparative analysis of offshore wind energy and mussel farming in the Belgian continental shelf with terrestrial alternatives. J. Clean. Prod. 470. https://doi.org/10.1016/j.jclepro.2024.143271.

Degraer, S., Carey, D., Coolen, J., Hutchison, Z., Kerckhof, F., Rumes, B., Vanaverbeke, J., 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: a synthesis. Oceanography 33 (4), 48–57. https://doi.org/10.5670/oceanog.2020.405.

Demuytere, C., Thomassen, G., Dewulf, J., 2025. Navigating towards environmental sustainability assessments of offshore wind farms at the end-of-life. Waste Manag. 205, 115016. https://doi.org/10.1016/j.wasman.2025.115016.

Desprez, M., 2000. Physical and biological impact of marine aggregate extraction along the French coast of the eastern English Channel: short- and long-term post-dredging restoration. ICES J. Mar. Sci. 57 (5), 1428–1438. https://doi.org/10.1006/jmsc.2000.0926.

Drew, J., 2011. Decommissioning Strategy. Gwynt Y Môr Offshore wind farm Ltd.

EAA, 2005. Environmental profile report for the European aluminum industry. In: Greenhouse Gas Protocol. Retrieved 28 May from. https://ghgprotocol.org/Third-Party-Databases/EAA.

Early, R., Bradley, B.A., Dukes, J.S., Lawler, J.J., Olden, J.D., Blumenthal, D.M., Gonzalez, P., Grosholz, E.D., Ibanez, I., Miller, L.P., Sorte, C.J., Tatem, A.J., 2016. Global threats from invasive alien species in the twenty-first century and national response capacities. Nat. Commun. 7, 12485. https://doi.org/10.1038/ncomms12485.

EPD International, 2024. Product Category Rules - Electricity, Steam and Hot/Cold Water Generation and Distribution: UN CPC 171 AND 173.

European Commission, 2010. International reference life cycle data system (ILCD) handbook - general guide for life cycle assessment - detailed guidance. In: An EU Strategy to Harness the Potential of Offshore Renewable Energy for a Climate Neutral Future, 2020.

European Commission, 2021. Commission Recommendation of 16.12.2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations.

European Commission, 2025. European Marine Observation and Data Network (EMODnet) Map Viewer. Retrieved 4 March from. https://emodnet.ec.europa.eu/geoviewer/#!/.

Fowler, A.M., Jørgensen, A.-M., Svendsen, J.C., Macreadie, P.I., Jones, D.O.B., Boon, A. R., Booth, D.J., Brabant, R., Callahan, E., Claisse, J.T., Dahlgren, T.G., Degraer, S., Dokken, Q.R., Gill, A.B., Johns, D.G., Leewis, R.J., Lindeboom, H.J., Linden, O., May, R., Coolen, J.W.P., 2018. Environmental benefits of leaving offshore infrastructure in the ocean. Front. Ecol. Environ. 16 (10), 571–578. https://doi.org/10.1002/fee.1827.

Galparsoro, I., Menchaca, I., Garmendia, J.M., Borja, Á., Maldonado, A.D., Iglesias, G., Bald, J., 2022. Reviewing the ecological impacts of offshore wind farms. npj Ocean Sustain 1 (1). https://doi.org/10.1038/s44183-022-00003-5.

Glasson, J., Durning, B., Welch, K., Olorundami, T., 2022. The local socio-economic impacts of offshore wind farms. Environ. Impact Assess. Rev. 95. https://doi.org/10.1016/j.eiar.2022.106783.

Hall, R., João, E., Knapp, C.W., 2020. Environmental impacts of decommissioning: onshore versus offshore wind farms. Environ. Impact Assess. Rev. 83. https://doi.org/10.1016/j.eiar.2020.106404.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment: Theory and Practice. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3.

Heery, E.C., Bishop, M.J., Critchley, L.P., Bugnot, A.B., Airoldi, L., Mayer-Pinto, M., Sheehan, E.V., Coleman, R.A., Loke, L.H.L., Johnston, E.L., Komyakova, V., Morris, R.L., Strain, E.M.A., Naylor, L.A., Dafforn, K.A., 2017. Identifying the consequences of ocean sprawl for sedimentary habitats. J. Exp. Mar. Biol. Ecol. 492, 31–48. https://doi.org/10.1016/j.jembe.2017.01.020.

Henley, J., 2023. European countries pledge huge expansion of North Sea wind farms. In: The Guardian. Retrieved 18 June from. https://www.theguardian.com/environment/2023/apr/24/european-countries-pledge-huge-expansion-of-north-sea-wind-farms.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2016. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22 (2), 138–147. https://doi.org/10.1007/s11367-016-1246-y.

IISI, 2005. IISI life cycle inventory study for steel industry products. In: Greenhouse Gas Protocol. Retrieved 28 May from. https://ghgprotocol.org/Third-Party-Databases/IISI.

ISO, 2006a. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. International Organization for Standardization.

ISO, 2006b. ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization.

Johansen, K., 2019. Local support for renewable energy technologies? Attitudes towards local near-shore wind farms among second home owners and permanent area residents on the Danish coast. Energy Policy 132, 691–701. https://doi.org/10.1016/j.enpol.2019.04.027.

Machado, J.T.M., de Andrés, M., 2023. Implications of offshore wind energy developments in coastal and maritime tourism and recreation areas: an analytical overview. Environ. Impact Assess. Rev. 99. https://doi.org/10.1016/j.eiar.2022.106999.

OSPAR Commission, 1998. OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations.

Prevost, M., Ladenburg, J., Soytas, U., Frost, J.K., Genin, A., Lang, R., Andersen, S.I., Vest, M.R., Hein, M., Nick, H.M., 2022. BIFROST, an innovative CO2 transportation and storage project in Denmark. In: 16th International Conference on Greenhouse Gas Control Technologies, Lyon, France.

Spielmann, V., Dannheim, J., Brey, T., Coolen, J.W.P., 2023. Decommissioning of offshore wind farms and its impact on benthic ecology. J. Environ. Manag. 347, 119022. https://doi.org/10.1016/j.jenvman.2023.119022.

Stephens, S., Robinson, B.M.K., 2021. The social license to operate in the onshore wind energy industry: a comparative case study of Scotland and South Africa. Energy Policy 148. https://doi.org/10.1016/j.enpol.2020.111981.

Stranddorf, L., Ladenburg, J., Zuch, M., 2025a. Tipping the Decision of Offshore Wind Farm Decommissioning – The Causal Effects of Biodiversity Illustrations and Information on the Social Acceptance. *Manuscript under Review*.

Stranddorf, L., Verones, F., Olsen, S.I., 2025b. Benefits and impacts of offshore wind farms on benthic marine biodiversity in a life cycle assessment context. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-025-02504-0.

Vattenfall, 2023. How Horns Rev 1 Paved the Way for Offshore Wind. Retrieved 26 May from. https://group.vattenfall.com/press-and-media/newsroom/2023/how-horns-rev-1-paved-the-way-for-offshore-wind.

Vattenfall, 2025. EPD of Electricity from Vattenfall's Wind Farms - EPD-IES-0001435:005 (S-P-01435).

Vetters, J., Thomassen, G., Van Passel, S., 2025. Getting stakeholders aboard for offshore wind decommissioning: a qualitative study on end-of-life challenges in Belgium. Energy Res. Soc. Sci. 120, 103873. https://doi.org/10.1016/j.erss.2024.103873.

Wagner, H.-J., Baack, C., Eickelkamp, T., Epe, A., Lohmann, J., Troy, S., 2011. Life cycle assessment of the offshore wind farm alpha ventus. Energy 36 (5), 2459–2464. https://doi.org/10.1016/j.energy.2011.01.036.

Watson, S.M., McLean, D.L., Balcom, B.J., Birchenough, S.N.R., Brand, A.M., Camprasse, E.C.M., Claisse, J.T., Coolen, J.W.P., Cresswell, T., Fokkema, B., Gourvenec, S., Henry, L.A., Hewitt, C.L., Love, M.S., MacIntosh, A.E., Marnane, M., McKinley, E., Micallef, S., Morgan, D., Macreadie, P.I., 2023. Offshore decommissioning horizon scan: research priorities to support decision-making activities for oil and gas infrastructure. Sci. Total Environ. 878, 163015. https://doi.org/10.1016/j.scitotenv.2023.163015.

Weidema, B.P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O., Wernet, G., 2013. *Overview and methodology: Data quality guideline for the ecoinvent database version 3* (Ecoinvent Report, Issue).

Whitehouse, R.J., Harris, J.M., Sutherland, J., Rees, J., 2011. The nature of scour development and scour protection at offshore windfarm foundations. Mar. Pollut. Bull. 62 (1), 73–88. https://doi.org/10.1016/j.marpolbul.2010.09.007.