Environmental Impact Assessment for the decommissioning of offshore wind farms

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Abstract

The rapid growth of renewable energy developments, particularly offshore wind, means that worldwide there are hundreds of artificial structures in the marine environment that will at some point require removal. Decommissioning activities can have a range of effects on the environment, which are assessed through an Environmental Impact Assessment (EIA) prior to removal. EIA provides an opportunity to explore the best environmental options for decommissioning if utilised early in the planning process during the wind farm design. EIA should be utilised as a decision-aiding tool to assess impacts and design mitigation and monitoring across the life of an asset. In this paper, potential environmental impacts, mitigation measures, and alternative actions are explored as examples of best environmental practice-based thinking at a range of scales and for multiple receptors. The removal of structures might be challenging with regards to best environmental options if countries require changes to policy. We pose alternative actions to be considered in EIA which take circular economy into account and maximise environmental benefit in the long term. To enable the best environmental outcomes, we propose that EIA should be used proactively and reflectively with a tailored approach to designing decommissioning.

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Keywords

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Environmental Impact Assessment, Offshore Wind, Decommissioning, Ecosystem Impacts, Circular Economy

Highlights

- EIA aids decision-making for best environmental practice for decommissioning
- Adverse decommissioning impacts can be mitigated by early planning and design
- Decommissioning can be environmentally beneficial but many need policy changes
- Wind farm design with a circular economy mindset may minimise impact of materials

List of abbreviations

EIA - Environmental Impact Assessment

IAIA - International Association for Impact Assessment

NEPA - National Environmental Policy Act

NNL - No Net Loss

NPI - Net Positive Impact

SWOT - Strengths, Weaknesses, Opportunities, and Threats

1. Introduction

Renewable energy has rapidly developed across the globe over the past few decades, while the seriousness of climate change continues to increase and the reliance on fossil fuels decreases. Due to this, offshore wind energy is a main contributor to the renewable energy mix. However, wind farms are temporary installations that require decommissioning at the end of their operational life. Less than 10 offshore wind farms have been decommissioned worldwide by 2021 [1] and thus, there is limited standardisation or protocols to follow.

Environmental Impact Assessments (EIA) is a decision-aiding tool used to help make the best possible decision with regards to avoiding or minimising impacts, and also contribute to net biodiversity gain [2]. EIA allows the evaluation of different options or scenarios to try and decide the best possible course of action. The premise for this paper is that the decommissioning of offshore wind farms can also benefit from the use of EIA.

The process of decommissioning can have a range of negative impacts on the environment, from disturbing the seabed, to materials going to landfill. Further, new marine habitats can establish around the structures which are then destroyed upon removal. Partial decommissioning may, however have positive effects as habitats are retained and local biodiversity enhanced as suggested by Hernandez et al. and Molen et al. [3, 4]. A good evidence base is required to predict effects and make informed choices over decommissioning activities, and not just at an individual species level, but encompassing ecosystem effects [5]. EIA is required prior to decommissioning, and also earlier in the development stage, and provide an opportunity to explore options for decommissioning based on best environmental practices.

This paper discusses the opportunities provided by EIA for the decommissioning of offshore wind farms using a best practice approach. This includes the impacts of removing the structures and associated activities, like vessel movement. Considering a range of scales and multiple receptors, the paper also discusses mitigation measures and explores alternative actions as examples of best environmental practice.

The paper starts by presenting the methods used, followed by an overview of EIA. The paper then analyses in detail the possible impacts of decommissioning offshore wind farms and the cumulative and in-combination effects, and evaluates the destination of removed components in order to try and achieve the maximum benefit and minimum impact. The paper concludes with recommendations, including actions with regards to data gaps.

2. Method for analysing the environmental impact of decommissioning activities

In order to analyse the environmental impact of offshore wind farm decommissioning, an extensive literature review was carried out using Google Scholar, ResearchGate, and Scopus. The review aimed to analyse the potential impact to different environmental receptors by the decommissioning of offshore wind farms, the scale at which impacts might occur, and opportunities provided by EIA. The receptors identified included physical processes, benthic ecology, fish, marine mammals, ornithology, other organisms, and the fate of materials.

The impacts were split by the decommissioning of the different elements of an offshore wind farm for above-sea and below-sea structures, for turbines and substations, and taking into account monopile, jacket, gravity-base, and suction bucket foundations, cables (array and export), and scour and cable protection (see Box 1).

Box 1 – Receptors and offshore wind farms components considered in this study

Environmental receptors:	**Offshore wind farms components:**

• Physical processes
• Benthic ecology
• Fish
• Marine mammals
• Ornithology
• Other organisms
• Materials
	• Above-sea structure (turbine and substation)
	• Below-sea structure (turbine and substation foundation):
	  - Monopile and jacket
	  - Gravity-base and suction bucket
	• Cables (array and export)
	• Protection (scour and cable)

Monopile and jacket foundations, and gravity-base and suction bucket foundations, are grouped based on installation and removal techniques likely required. Where pile-driven monopile and jackets require invasive removal or cutting, gravity-base and suction buckets allow full removal via lifting from the seabed [6].

The onshore components of offshore wind farms (from cable landfall to onshore substation) are not analysed here. The environmental aspects of these onshore components should additionally be considered, however may fall under different legislative and authority jurisdiction to the offshore counterpart.

The potential impacts of decommissioning an offshore wind farm assume the complete removal of each of the components previously mentioned. Most of the potential impacts from decommissioning are likely to be similar to those during the construction phase, for instance, noise disturbance to fish and marine mammals, and seabed disturbance from jack-up vessels.

The impacts of decommissioning the individual components on each receptor is analysed within this paper. Potential mitigation options and alternative actions are suggested as per the mitigation hierarchy [7], and consideration is given to the logistical and legislative requirements to allow such mitigation and alternative actions to be taken.

3. Opportunities provided by Environmental Impact Assessment

According to the International Association for Impact Assessment (IAIA), "impacts are changes that are judged to have environmental, political, economic or social significance to society. Impacts may be positive or negative and may affect the environment, communities, human health and well-being, desired sustainability objectives, or a combination of these" [8]. It is fundamental that EIA identifies both direct and indirect impacts. Indirect impacts are triggered by the project but affect the environment as a knock-on effect, which can be later in time or farther removed in distance from the project.

The EIA process examines the environmental consequences of a proposed activity or project in advance [9], such as the decommissioning of an offshore wind farm, in order to inform decision-making. This needs to be done in a transparent way with rich public participation. Public participation is not just about doing things in a democratic way by ensuring that the publics' views are adequately taken into consideration in the decision-making process, it is also about ensuring the quality, comprehensiveness and effectiveness of the EIA itself [10].

The main reason why EIA is done is to improve decision-making, because it is "better safe than sorry". For this reason, EIA spread quickly around the world since its inception in 1969 with the National Environmental Policy Act (NEPA). Now in hundreds of countries around the world, by law, EIA is needed before decisions are made. However, despite the legal requirements, EIA can be (and should be) used as a project design tool. This paper takes the EIA according to a best practice approach, and therefore make it universally relevant.

EIA needs to be done for the whole lifecycle of a project: design, construction, operation and decommissioning stages. Thus, when an EIA is done for the proposal of a new wind farm, the EIA should already have considered the impacts of decommissioning. However, it is important to assess how the project might have altered the baseline and how the value of the receptors might have changed over the life of the wind farm [11]. It is possible as well that the buried cables are now much deeper. Therefore, the EIA that was performed before the wind farm was approved for construction might not be sufficient to determine the decommissioning impacts, and now a new EIA might be needed to focus just on the decommissioning alternatives.

Scoping identifies, from all of the possible impacts and alternatives, those that are the potentially key, significant issues. Significance is about assessing the relative importance of the predicted impacts [12]. It is not just size or magnitude of the impact that determines its significance. It also depends on the sensitivity of receiving environment, and the duration, periodicity, reversibility, spatial incidence and probability of the impact. The notion of carrying capacity and ecological limits is important here. A small size impact that may nevertheless cause a system to go over the carrying capacity and over ecological limits will be extremely significant, despite the small impact magnitude.

The evaluation of key impacts and their significance will then inform what mitigation measures may be needed. The mitigation hierarchy states that environmental damage must first be avoided, before being minimised or reduced, then compensated as a last resort. This precautionary approach [13] is applied through the EIA process by thinking of decisions assuming a worst-case scenario. Importantly, an environmental-based design would consider not only the mitigation of negative environmental impacts (i.e. making changes to avoid adverse effects) but, innovatively, it would also consider the enhancement of positive impacts [14]. With regards to biodiversity, some organisations and governments are now aiming for “net positive impact” (NPI) rather than just a “no net loss” (NNL) [15].

Finally, EIA follow-up is fundamental in order to monitor the impacts, and to ensure that mitigation and enhancement measures have been done and, very importantly, they are working. Follow-up refers to the monitoring, evaluation, management and communication of the environmental performance of a project [9, 16].

Another aspect that may need to be considered in the EIA of decommissioning is social closure planning, when people are directly and indirectly dependent on the activity being closed down for their livelihoods. For example, this is very important with regards to the closure of mining activities in developing countries [17]. This paper, however, focuses on the physical and bio-physical aspects of decommissioning, which are now discussed in the next section.

4. Impacts of decommissioning offshore wind farms

This section reviews some of the potential impacts that the decommissioning of offshore wind farms might pose. It is split by the receptor potentially impacted and components of the wind farm to be decommissioned (see Box 1 in section 2). Generic potential mitigation actions are suggested for the impacts. Alternative actions that would reduce or remove the impacts are further suggested.

This section is not designed to be an exhaustive list of all potential impacts and mitigation techniques, but a suggestion of aspects of the environment to consider during an EIA and promotion of best environmental practice-based thinking. Although the section is split by receptors, it is important to remember that many aspects of the natural environment are linked and interact, for instance, through competition, predation, herbivory and symbiosis [18].

4.1 Decommissioning impacts associated with physical processes

The effect of offshore wind farm decommissioning on physical processes might include changes to seabed morphology, sediment movements, and water quality. The impacts to this receptor is likely to be much the same as those present during the construction phase. The removal of substructures, including different foundation types, cables, scour protection, and cable protection has the potential to cause changes in the movement of sediments, mobilise contaminants, fluidise sediments which may travel and subsequently be deposited potentially smothering habitats, and increase turbidity. However, there may be possible mitigation techniques to avoid or minimise these impacts, such as using methods that reduce disturbance to the seabed, testing the material that will be removed, and undertaking work under tidal conditions to reduce smothering of important habitats (Table 1).

Table 1. Decommissioning impacts, mitigation and alternatives for physical processes

Possible impact due to decommissioning offshore wind farm	**Possible mitigation or alternative action during decommissioning offshore wind farm**	**How impact and/or mitigation may vary**	**Above sea structure**	**Below-sea structure (turbine and substation foundation)**		**Cables**	**Protection**
				Monopile &	Gravity-base & suction		
Changes to sediment movements	• Systems with reduced disturbance to seabed [a]	• Type of seabed • Removal methodologies available		✓	✓	✓	✓
Mobilisation of contaminants	• Testing of seabed and material to be removed	• Type of seabed • Removal methodologies available		✓	✓	✓	✓
Fluidisation of seabed and smothering of habitats	• Systems with reduced disturbance to seabed [a] • Undertaking work under tidal conditions to reduce smothering of important habitats	• Type of seabed • Removal methodologies available • Surrounding habitats		✓			✓
Increased turbidity	• Systems with reduced disturbance to seabed [a]	• Type of seabed • Removal methodologies available		✓	✓	✓	✓

[a] For instance, cutting structures instead of vibratory removal which may disturb sediment, whilst noting that this method may have adverse noise impacts.

4.2 Decommissioning impacts associated with benthic ecology

This section describes potential impacts to benthic ecology: the flora and fauna living in, on, or near the seabed. As observed by Krone et al., the presence of structures in the marine environment often generates new habitats for organisms to colonise, including on the foundations, cables, and scour and cable protection [19]. Structures such as these are not usually encountered in the marine environment besides coastal areas where coastal protection and harbours are present. Therefore, there is the potential for the vast expansion of species colonising structures with a knock-on effect to ecosystem services which such species provide, such as seawater filtration from colonisation of the blue mussel *Mytilus edulis* in the North Sea [20].

There are a range of pathways between effects to benthos and the processes which support ecosystem services [21], but it is currently unclear whether these are positive or negative, or indeed neutral [22]. Regardless, the removal of the structures promoting these changes is again likely to cause changes [23]; the exact nature of these should be assessed through the EIA process. Some of the potential impacts to benthic ecology are listed in Table 2. The removal of foundations and protection structures is likely to lead to habitat loss, though the impact of such removal may depend upon how important the structures are to organisms that utilise them, directly or indirectly, among other things. Where habitats are of importance, the retention of structures may mitigate such loss, allowing any positive benefits of the presence of structures to continue.

Table 2. Decommissioning impacts, mitigation and alternatives for benthic ecology

Possible impact due to decommissioning offshore wind farm	**Possible mitigation or alternative action during decommissioning offshore wind farm**	**How impact and/or mitigation may vary**	**Above sea structure**	**Below-sea structure (turbine and substation foundation)**		**Cables**	**Protection**
				Monopile &	Gravity-base & suction		

Habitat loss	• Retaining all or partial foundations	• How important the structures are to the flora and fauna which use them		✓	✓		✓
Introduction of new material to fill voids	• Use of material compatible with local benthic community [a]	• Changes in local environment		✓		✓	✓

[a] For instance, creating an environment similar to or compatible with the surrounding habitat.

4.3 Decommissioning impacts associated with fish

During the construction and operation of offshore wind farms, fish are often sensitive to the noise generated from construction activities and the presence of vessels. During decommissioning, it is likely that a similar level of noise from vessels will occur. The noise from decommissioning activities and likelihood of significant effects on sensitive receptors will depend upon the method of structure removal selected. As with construction, the response of sensitive receptors such as fish will also be dependent on the distance to the noise source and the duration of exposure [24]. Similar mitigation techniques may also therefore be employed, such as gradually increasing the noise level to allow individuals to move to a safe distance from the source, bubble curtains, and implementing timing restrictions to take account of life history of sensitive species [25] (Table 3).

The removal of structures during decommissioning has the potential to cause a further impact through the removal of habitat; for fish this may have two-fold implications. There is some consensus, as discussed by Nehls et al., that structures in the marine environment create foraging opportunities and shelter, whilst at the same time protecting ecosystems from fishing [26], thus the removal of these structure has the potential to remove both foraging and protective areas.

Table 3. Decommissioning impacts, mitigation and alternatives for fish

Possible impact due to decommissioning	**Possible mitigation or alternative action during decommissioning offshore wind farm**	**How impact and/or mitigation may vary**	**Above sea**	**Below-sea structure (turbine and substation foundation)**	**Cables**	**Protectio**

offshore wind farm				Monopile &	Gravity-base & suction		
Habitat loss	• Retaining all or partial foundations	• How important the structures are to the flora and fauna which use them		✓	✓		
Underwater noise (removal of foundation)	• Systems with reduced noise emissions [a]	• Dependent on the structure to be removed		✓	✓		✓
Underwater noise (vessels)	• Vessels with lower noise emissions • Undertaking work outside of important times for sensitive species	• Dependant on habituation to vessel noise in the area		✓	✓	✓	✓

[a] For instance, the use of cutting tools with lower noise levels. The use of soft start procedure to gradually increase noise levels to allow individuals to move away from the noise source. The use of protective measures such as bubble curtains. A review of noise mitigation techniques can be found in [27].

4.4 Decommissioning impacts associated with marine mammals

Similar to fish, marine mammals can be sensitive to noise generated through construction and decommissioning activities, with hearing loss, displacement, and the masking of other sounds that have the potential to impact species [28]. Marine mammal response to noise may depend on the strength of the noise, the nature of the noise source, and its context in terms of the activity undertaken by an organism, amongst other factors [29].

The noise level emitted during decommissioning activities is likely to be dependent on the removal techniques used and the type of structure in place. The frequency of vessels movements and concurrent presence of marine mammals may habituate some species to their occurrence. However, Marques et al. note that persistent increases of anthropogenic noise in the marine environment is having an incremental detrimental impact to organisms [30].

Mitigation techniques can be used to reduce the impact, such as reducing noise emissions or noise propagation, and undertaking work outside important times for noise-sensitive species (Table 4). During operation, however, Todd et al. found that marine mammals frequented anthropogenic structures, taking advantage of aggregations of prey species [31]. The relative importance of these foraging locations and the result of removing them during decommissioning is as yet unknown.

Table 4. Decommissioning impacts, mitigation and alternatives for marine mammals

Possible impact due to decommissioning offshore wind farm	**Possible mitigation or alternative action during decommissioning offshore wind farm**	**How impact and/or mitigation may vary**	**Above sea structure**	**Below-sea structure (turbine and substation foundation)**		**Cables**	**Protection**
				Monopile &	Gravity-base & suction		
Underwater noise (removal of foundation)	• Systems with reduced noise emissions [a]	• Dependent on the structure to be removed		✓	✓		
Underwater noise (vessels)	• Vessels with reduced noise emissions	• Dependent on habituation to vessel noise in the area	✓	✓	✓	✓	✓
Collision with vessels	• Undertaking work outside of important times for sensitive species	• Dependent on habituation to vessel activity in the area	✓	✓	✓	✓	✓

[a] For instance, the use of cutting tools with lower noise levels. The use of soft start procedure to gradually increase noise levels to allow individuals to move away from the noise source. A review of noise mitigation techniques can be found in [27].

4.5 Decommissioning impacts associated with ornithology

A range of potential impacts to ornithology exists during the construction and operation of offshore wind farms, some of which are also relevant during decommissioning. For instance, the impact of disturbance and displacement by vessel movements is likely to be similar to that during construction activities. Therefore, similar mitigation might also be used, such as undertaking work outside of important times for sensitive species, as proposed by Langhammer [32].

Similar to benthic ecology and fish, ornithology may be affected by the removal of structures and associated habitats, areas for foraging, and loss of prey species; again, these effects might be minimised or avoided by retaining structures of importance to the species in question (Table 5). There are, however, potential benefits to the removal of above-sea structures. The risk of bird collisions with wind turbines will be removed once the rotor is removed. Even repowering wind turbines could be beneficial where problematic turbines are relocated or larger turbines are installed higher above the sea as noted by Thomsen and Verfuss [33].

Table 5. Decommissioning impacts, mitigation and alternatives for birds

Possible impact due to decommissioning offshore wind farm	**Possible mitigation or alternative action during decommissioning offshore wind farm**	**How impact and/or mitigation may vary**	**Above sea structure**	**Below-sea structure (turbine and substation foundation)**		**Cables**	**Protection**
				Monopile &	Gravity-base & suction		
Disturbance and displacement by vessels	• Vessels with reduced noise emissions • Undertaking work outside important times for sensitive species	• Dependant on habituation to vessel activity in the area	✓	✓	✓	✓	✓
Loss of habitat for foraging	• Retaining all or partial foundations	• How important the structures are to the flora and fauna which use them		✓	✓		
Reduced prey availability	• Retaining all or partial foundations	• How important the structures are to the flora and fauna which use them		✓	✓		✓
Disturbance to sensitive species at cable landfall	• Undertaking work outside of important times for sensitive species	• Dependant on habituation to vessel activity in the area				✓	

4.6 Decommissioning impacts associated with other organisms

The presence of offshore wind farms has the potential to create beneficial artificial reefs, increasing biodiversity locally with spill-over effects to areas beyond the wind farm [34]. However, species attraction may not always result in the same assemblages as those that would occur naturally, casting some doubt upon how positive an impact might be [35], especially where non-indigenous species are prevalent [34]. Nonetheless, as discussed by Perkol-Finkel and Benayahu, artificial reefs may be more beneficial for biodiversity if new communities are generated, rather than simply transplanting species into the wind farm from the surrounding area [36].

Regardless of the type of ecological change, the impact that structure removal might have should be analysed; the impact of removal may be positive or negative based on the impact of the structure present. Where important or endangered species utilise the structures or such species might be adversely impacted by decommissioning activities, potential alternative actions should be considered, such as retaining structures important to the species and appropriately timing works (Table 6). Monitoring of the ecology of a wind farm is crucial to understand the organisms present and prevent adverse harm to endangered or protected species, especially where such protection is legally required, for instance, under the European Habitats Directive 92/43/EEC.

Table 6. Decommissioning impacts, mitigation and alternatives for other organisms

Possible impact due to decommissioning offshore wind farm	**Possible mitigation or alternative action during decommissioning offshore wind farm**	**How impact and/or mitigation may vary**	**Above sea structure**	**Below-sea structure (turbine and substation foundation)**		**Cables**	**Protection**
				Monopile &	Gravity-base & suction		
Indirect impacts to local productivity and biodiversity from	• Retaining all or partial foundations	• How important the structures are to the flora and fauna which use them		✓	✓		✓

removal of habitat							
Threat to threatened or endangered species	• Retaining all or partial foundations • Undertaking work outside of important times for sensitive species	• How important the structures are to the flora and fauna which use them • Removal technique used		✓	✓		✓

4.7 Decommissioning impacts associated with materials

The impact of materials generated as a result of decommissioning activities also needs to be considered. For instance, the ability for materials to be re-used or recycled; this is especially important where composite material is used, often in the nacelle and cables. The potential for generation of hazardous materials and dust during decommissioning activities must also be considered [37]. These aspects can be mitigated through the use of appropriate methodologies at the decommissioning stage, though consideration of decommissioning and the fate of materials during wind farm design may help minimise this impact from the outset by using a circular economy mindset [38] (Table 7). The potential for pollution and the impact it might have on the environment is another consideration, though this is likely to be covered by an environmental management plan.

Table 7. Decommissioning impacts, mitigation and alternatives associated with materials

Possible impact due to decommissioning offshore wind farm	**Possible mitigation or alternative action during decommissioning offshore wind farm**	**How impact and/or mitigation may vary**	**Above sea structure**	**Below-sea structure (turbine and substation foundation)**		**Cables**	**Protection**
				Monopile &	Gravity-base & suction		
Dust from cutting fibre glass and carbon fibre blades	• Design with circular economy in mind [a]	• Methodologies available	✓				
Issues reusing, recycling	• Design with circular economy in mind [a]	• Methodologies available	✓			✓	

and/or disposing of composite materials							
Pollution	• Appropriate systems to prevent spillages	• Nature of hazard	✓				

[a] For instance, designing components such that they can be dismantled and disassembled, and then parts re-used or recycled once they are no longer required.

4.8 Overview of the decommissioning impacts at different scales

It is important to note that the reef effect at offshore wind farms can be important at various scales: micro, meso, and macro. At the micro scale, the construction material can influence the epibenthic communities that live upon it, whilst at the meso scale, zonation from the seabed up to the sea surface can influence the organisms that inhabit a wind farm. On a wider spatial scale, Petersen and Malm observe that the distribution of individual turbines throughout a habitat may present varying local environments [39]. The expansion of renewable energy developments in the southern North Sea, for instance, has the potential to create 4.3 times more hard bottom habitats than currently exists [20]. These different scales of change must be taken into consideration to ensure that the EIA study area coincides with the potential area of impact. Artificial reefs may also have benefits at different life stages of organisms, as noted by Glarou et al., for example as nursery grounds, for reproduction, shelter, and foraging areas for fish species [40].

Importantly, there is evidence that a disturbed environment may not fully recover to its pre-disturbed state, even where active recovery is implemented [41]. Therefore, it is debatable that the requirement to remove structures will restore the environment to its pre-construction state [40, 41], and what a ‘reversible’ impact really means in practice as discussed by Windemer and Cowell [42]. However, enhancing the marine environment through artificial reefs and marine protected areas in places where anthropogenic disturbance has had a negative impact can generate a positive outcome [43]. Opportunities may also arise to allow structures to be designed the marine environment in mind, if it is permitted that strategic components or parts of wind farms can be retained on the environment once operation has ceased.

Consideration should further be given to all options of removal and retention of structures. A SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) of the removal of all structures versus the partial removal carried out by Smyth et al. [44] found that it may be more beneficial to retain some offshore wind farm structures within the marine environment given the costs and safety associated with removal. This is especially true where protection and enhancement of the environment is required and can be attained. For instance, providing refuges for certain species by creating holes and increasing habitat complexity has shown a rise in the occurrence of crab species [45].

Scour protection is often required at offshore wind turbines where there is a risk of erosion of the surrounding soft sediment, and where cables protrude above the seabed. There are various types of scour protection available, many of which mimic natural environments [46]. A mix of scour protection might further increase the diversity of habitats proving additional gains for biodiversity, especially where scour protection has the potential to generate 2.5 times the habitat lost through placement of turbines [46]. Therefore, where the retention of scour protection is considered at the design stage, an opportunity arises to tailor these materials for beneficial long-term benefit to the local environment. Conversely, it may not be environmentally beneficial to retain all turbine foundations, especially if non-indigenous or invasive species are attracted [47]. Regardless, the full impact (positive and negative) of a range of decommissioning, removal, and retention options should be fully assessed and considered early in the decision-making process, particularly where structures can be modified specifically for environmental enhancement.

5. Cumulative and in-combination effects

It is important to also discuss the potential cumulative and in-combination effects as a result of offshore wind farm decommissioning. Cumulative effects describe the multiple effects from many developments of the same type, whilst in-combination effects occur where different types of plans and/or projects combine to affect a receptor.

Cumulative effects can be the same type of effect from several wind farms, such as displacement from many renewable energy areas, or the accumulation of different types of effects on a receptor, such as collision risk and noise disturbance. In-combination effects depend not only on the activities at the site of one activity, but also on the other activities likely to affect the receptor in question. Both cumulative and in-combination effects may vary based on the spatial and temporal scale of the effects from the project of focus, other projects of a similar type, and other industries, as well as across different phases of development [48].

A key in-combination and cumulative effect from the existence of offshore wind farms is that of reef effects. At an individual wind farm level, effects may start from the upwelling of nutrients caused by a wind farm’s effect on the local wind. This upwelling can cause increased primary production with the size of a wind farm as discussed by Broström et al. [49], resulting in impacts to numerous species across trophic levels, which are affected by different aspects of the wind farm and different stages of its life. These changes across tropic levels potentially have local ecosystem impacts which may interact with those impacts from other wind farms [4]. Nonetheless, without quantifying these effects in the same units, such as population reproductive rate, the consequences of in-combination and cumulative effects are difficult to predict [50].

Cumulative impacts are notoriously difficult to predict and assess; the uncertainty surrounding them can cause delays to offshore windfarm consent and development as found by Masden et al. [51]. However, collaboration on data collection and assessment across developments is one method of improving uncertainties [52]. Attempts to quantify the cumulative effects of offshore wind farms on a range of receptors have been made, and show where hotspots of cumulative effects may occur, particularly across the North Sea [48].

Although decommissioning represents a relatively small predicted effect, cumulatively with other projects that are operation have the potential to be cumulatively significant.

6. Destination of removed components for maximum benefit and minimum impact

An important decision when planning decommissioning is to designate what to do with the structures once removed and is where the Zero Waste Hierarchy should be considered. The Zero Waste Hierarchy is a set of priorities for the efficient use of resources as specified in Box 2 [53, 54].

Box 2 - Priorities for efficient use of resources according to the Zero Waste Hierarchy [50]

1. **Rethink or redesign**: Using reused, recycled or sustainably harvested products within the design products. Ensure that products are built to last, be repairable, and easily disassembled.
2. **Reduce**: It encourages reducing the amount of waste generated by maximising efficiency and avoiding unnecessary consumption of raw materials.
3. **Reuse**: Maximising options for re-use (without further processing) keeps materials in the productive economy and benefits the environment by decreasing the need for new materials and waste absorption.
4. **Recycle**: Maximising options for recycling, processing waste materials to make the same or different products to get the most use of out materials.
5. **Recovery**: Recover the energy from the material and feed energy back into the economy.
6. **Residuals management**: Responsible management of leftover materials, and use knowledge gained from them to refine rethinking, reducing, reusing, and recycling to prevent further residuals.
7. **Disposal**: Some types of waste, such as hazardous chemicals or asbestos, cannot be safely recycled and direct treatment or disposal is the most appropriate management option.

Therefore, it is critical to design the projects to maximise the value of resources and, in the process, reduce the end of life waste generated. Once the life of the asset ends, it is necessary to foresee the measures that need to be implemented to valorise all of the components and to minimise the overall environmental impact. Thus, while searching for the optimal solution, Topham and McMillan argued that not only costs, but also sustainability, should be a deal breaker [6]. There are several options that can be considered once the end of life of a project is approaching. These can range from the refurbishment of certain elements to a complete decommissioning, highlighting that reusing should be prioritised and, only if not possible to reuse, should recycling be done.

Refurbishment (or partial repowering), consists of the reuse, repair or replacement of elements of the project, to increase its operational lifetime, efficiency, and consequently, energy production. Nevertheless, in the end, certain decommissioning is required as elements are removed [55].

Full repowering entails the re-use of as much available installation as possible, such as the electrical system and/or foundations, while installing more powerful turbines. Foundations can be designed to last longer than the 20-25 years of the wind turbines, whilst the estimated lifetime of a gravity-based foundations is 100 years [6]. This is also the case for the electrical system (inter-array and transmission lines), which is estimated to be 40 years [56, 57]. Nonetheless, it has to be noted that these estimations are difficult to forecast as every project has its own characteristics that will determine the loading factors and aging of the asset [55].

Lifetime extension is the widening of the operational life of the asset and is only possible if wind turbines have enough structural life remaining so that the safety level is not compromised. This alternative will inevitably lead to any other of the above mentioned [55].

Decommissioning is recognised as the most important of all the end of life strategies, as all the other strategies will end either way, leading into this stage. Usually, once the asset ceases operation, there is a requirement that the site must be left as it was before the deployment of the project. The "polluter pays" principle is regularly used as the reason for requesting that the site is restored, which also includes a two-year period of monitoring and remediation [55]. The "polluter pays" principle aims to prevent and remedy environmental damage, however as there is limited and unclear regulations regarding this topic there is controversy surrounding the fate of these offshore structures due to the possible establishment of new habitats. As the removal of structures may cause ecological damage to natural habitats or protected species, the "polluter pays" principle may require the structures to be retained. This would be, as well, beneficial for the project owners, as they would have significant cost savings (i.e. foundations, buried cable removal). However, this could happen anyway and under worse scenarios if project owners do not save appropriate cash amounts for this final stage [57], being a current government concern nowadays [58].

Due to this, and understanding that the turbines, foundations and the substation will be removed, the reuse or recycling of components is fundamental. To minimise the environmental impacts during the decommissioning operations, embedded foundations can be cut a few metres into the seabed while leaving the rest *in situ*, as its complete removal could produce significant marine disruption and costs. The same applies to the electrical system if it is correctly buried [6].

As the reuse of components is a priority after the option for designing in the search of waste reduction, a second-hand market for used turbines and spare parts has emerged. This eases the options for refurbishment and repowering while reducing the costs of the components, or just enables the relocation of turbines to be used in other countries.

If reusing is not possible, then recycling measures should be adopted. Approximately 95% of wind turbines can be recycled as they are mainly manufactured from metals, which are used in the tower, the gearbox, the main shaft, the generator, castings, bearings and parts from the nacelle and hub. Moreover, foundations are also generally made from steel which increases this recycling value [57]. Recycling not only enhances sustainability but can also reduce decommissioning costs by 20%, although this will mainly depend on the scrap prices at that time [55].

Regarding the remaining 5%, it mainly consists of power electronics, lubricant and cooling substances, and polymers that principally come from blades. Blades are currently very problematic to recycle and have become the main challenge from a recycling and logistical perspective [57], therefore are just being shredded and disposed. Due to this, and the high margin of improvement available, there is currently a lot of ongoing research [58].

As wind turbines are continuously growing in size, the evolution of offshore wind turbines could be negatively impacted while becoming less sustainable due to the amount of raw materials required. This is because the quantity of raw material used in an equivalent turbine capacity for a single larger turbine is higher than for two smaller ones. This means that as installing larger offshore wind turbines is the current tendency, an increased use of raw materials could compromise the sustainability of the sector [57] and therefore designing for waste reduction, reusing and recycling measures are essential.

7. Future recommendations for offshore wind farm decommissioning

The actions taken during design and planning, despite them occurring many years before the end of life of a wind farm, are likely to impact the decisions taken during decommissioning. In addition, the presence of structures can alter the surrounding habitat incidentally making changes that need to be considered at the end of life. If and where wind farms are designed to enhance the environment, the decommissioning of such wind farms might be detrimental. There may even be rationale for retaining structures that were designed for environmental improvement. Wind farms are sometimes described in environmental assessments as having an overall minor or negligible effect due to the offsetting of negative effects by virtue of reef effects [59]. These reef effects may, however, be removed during decommissioning and removal of structures. These negative, positive, and overall neutral effects may only be short-term (over the life of the wind farm), but there is potential for positive reef effects to have a longer lasting impact where structures are strategically left in place.

Many unknowns exist within offshore wind farm decommissioning, environmental effects included; these also extend to construction and operation. These gaps in data often result in difficulties predicting and assessing potential environmental effects and subsequently recommending actions. One area where such data gap exists is the long-term environmental changes brought about by the presence of offshore wind farms. Without this vital understanding, making best environmental practice recommendations for actions during decommissioning is difficult. Therefore, regular and consistent environmental monitoring is recommended, ideally throughout the operational life of a wind farm, rather than the beginning and the end alone. Collaboration and knowledge sharing across wind farm developers and operators will also advance understanding. It will become increasingly more important to understand the wider scale of environmental impacts, particularly when multiple projects have their own associated impacts and are at different stages of development, as renewable energy continues to grow.

Such modifications to the current standpoint of complete removal (besides any structures below the seabed) might come as a result of site investigations to determine if habitats and species of conservation importance are present which may require protection [44]. This might also assess the value of the ecosystem services provided by structures in the marine environment such as the contribution reef effects have to local conservation targets [26]. There is some suggestion that offshore wind farms act as de-facto marine protected areas and could be afforded formal designation, recognising the importance of reef effects to the wind farm and surrounding area. However, limited understanding of ecosystem-level effects currently restricts recommendations for their implementation [60]. Should such a zone be appointed a marine protected area, those undertaking any decommissioning activities would be responsible for preventing negative impacts to the designated features of the site or the site's integrity. Impacts may be exacerbated due to potential cumulative and in-combination effects caused by the decommissioning of offshore wind farms. Despite the challenge of determining these impacts, it is fundamental that they are accounted for.

Consideration of the Zero Waste Hierarchy at the earliest stage of development is crucial in order for renewable energy generation to be sustainable, particularly as structures become larger in size and require more raw and recycled material. A balance needs to be struck between the various environmental, economic, and social aspects of building, life-extending, and decommissioning a wind farm [61], as well as safety to personnel and the environment, and feasibility of strategies [62]. With these topics gathering increasing attention as renewable energy targets grow and existing infrastructure ages, frameworks for the consideration of end-of-life strategies are emerging [42, 62-64].

Many of the suggested alternative actions in this paper aim to reduce or remove the potential impact of standard decommissioning actions. Some alternative actions may pose a best environmental option, yet policy and legislation in certain countries might not allow for them to be undertaken (e.g. in the UK it is recommended that all infrastructure will be removed; the only exception to this would be where removal presents unacceptable risks to personnel or the marine environment [65]). For many of these alternative actions to be implemented, a reform of the existing policy and legislation could be required. Offshore wind is still a relatively new technology, with guidance frequently updated based on past learning; the first decommissioning guidance from the UK government did not emerge until several years after the first wind farms were operational [66]. The continual modification of guidance and regulation allows the possibility of changes to legislation to be more flexible in retaining offshore structures in the future.

8. Conclusions

Many of the potential impacts associated with the decommissioning of offshore windfarms are similar to those during the construction phase. However, many of the potential impacts are likely to arise from the removal of the structures themselves: the removal of organisms occupying the structures and the fate of the structures, raising the question of whether impacts are ‘reversible’ and how this may depend on the baseline against which impacts are assessed [42]. Many of the suggested alternative actions stated in this paper aim to reduce or remove the potential impact of standard decommissioning actions. It is also important that thought is given to the destination of removed components. A Best Practicable Environmental Option approach to waste and pollution control is a good baseline method that aims to compare potential actions and generate a realistic option that provides the most environmental benefit or least environmental damage. In addition, projects should start with a design that enables a reduction in the end of life waste generated as it is essential to minimise the overall environmental impact. This is then followed by reusing and/or recycling measures that could even reduce the decommissioning costs. Nonetheless, due to the trend of installing larger turbines, sustainability could be comprised because of an increased use of raw materials.

The environmental impact of offshore wind farm decommissioning needs to be assessed, the same as many other large-scale developments. However, the decommissioning of projects has an advantage in that its environmental impact can be assessed both prior to decommissioning and at the design stage. EIA in this way allows for various scenarios to be analysed and decommissioning choice to be incorporated into the initial project design. It also provides opportunities to amend and reflect on the initial decommissioning approach, taking changes over asset's life into consideration and design a tailored decommissioning approach for the best environmental outcome.

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References

[1] T. Adedipe and M. Shafiee, "An economic assessment framework for decommissioning of offshore wind farms using a cost breakdown structure," *The International Journal of Life Cycle Assessment,* vol. 26, pp. 344-370, 2021.

[2] S. Brownlie, N. King, and J. Trewek, "Biodiversity tradeoffs and offsets in impact assessment and decision making: can we stop the loss?," *Impact Appraisal,* vol. 31, pp. 24-33, 2013.

[3] O. M. Hernandez, M. Shadman, M. M. Amiri, C. Silva, S. F. Estefen, and E. L. Rovere, "Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil," *Renewable and Sustainable Energy Reviews,* vol. 144, p. 110994, 2021, doi: 10.1016/j.rser.2021.110994.

[4] J. v. d. Molen, H. C. M. Smith, P. Lepper, S. Limpenny, and J. Rees, "Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem," *Continental Shelf Research,* vol. 85, pp. 60-72, 2014, doi: 10.1016/j.csr.2014.05.018.

[5] A. J. Lemasson, A. M. Knights, M. Thompson, G. Lessin, N. Beaumont, and C. Pascoe, "Evidence for the efects of decommissioning man-made structures on marine ecosystems globally: a systematic map protocol," *Environmental Evidence,* vol. 10, p. 4, 2021.

[6] E. Topham and D. McMillan, "Sustainable decommissioning of an offshore wind farm," *Renewable Energy,* vol. 102, pp. 470-480, 2017, doi: 10.1016/j.renene.2016.10.066.

[7] The Biodiversity Consultancy. "Mitigation Hierarchy: Net Positive And The Mitigation Hierarchy." https://www.thebiodiversityconsultancy.com/our-work/our-expertise/strategy/mitigation-hierarchy/ (accessed 23/03/2022.

[8] International Association for Impact Assessment, "Fastips No. 1: What is Impact Assessment?," 2012.

[9] A. Morrison-Saunders and L. Arts, "Assessing impact: Handbook of EIA and SEA Follow-Up," 2014.

[10] H. Kalle and L. den Broeder, "Fastips No. 10, Fargo: International Association for Impact Assessment," 2015. [Online]. Available: https://www.iaia.org/uploads/pdf/Fastips_10EffectiveStakeholderEngagement.pdf

[11] IEMA, "Environmental Impact Assessment Guide to Climate Change Resilience and Adaptation," 2015.

[12] J. Boyle and J. L. Barnes, "Assessing Significance in Impact Assessment of Projects', Fastips No. 14, Fargo: International Association for Impact Assessment," 2016. [Online]. Available: https://www.iaia.org/uploads/pdf/Fastips_14%20Significance_1.pdf

[13] K. Jalava, I. Pölönen, P. Hokkanen, and M. Kuitunen, "The precautionary principle and management of uncertainties in EIAs – analysis of waste incineration cases in Finland," *Impact Assessment and Project Appraisal,* vol. 31, pp. 280-290, 2013, doi: 10.1080/14615517.2013.821769.

[14] E. João, F. Vanclay, and L. Broeder, "Emphasising enhancement in all forms of impact assessment: introduction to a special issue," *Impact Assessment and Project Appraisal,* vol. 29, pp. 170-180, 2011.

[15] G. d. Silva, E. Regan, E. Pollard, and P. Addison, "The evolution of corporate no net loss and net positive impact biodiversity commitments: Understanding appetite and addressing challenges," *Business Strategy and the Environment,* vol. 28, pp. 1481-1495, 2019, doi: 10.1002/bse.2379.

[16] R. Marshall, J. Arts, and A. Morrison-Saunders, "International principles for best practice EIA follow-up," *Impact Assessment and Project Appraisal,* vol. 23, pp. 175-181, 2005, doi: 10.3152/147154605781765490.

[17] A. Morrison-Saunders, "The action is where the social is! The ecosystem services concept and other ideas for enhancing stakeholder engagement in integrated mine closure planning," in *Proceedings of the 13th International Conference on Mine Closure*, 2019, pp. 5-18, doi: 10.36487/ACG_rep/1915_02_Morrison-Saunders. [Online]. Available: https://doi.org/https://doi.org/10.36487/ACG_rep/1915_02_Morrison-Saunders.

[18] J. Lang and M. Benbow, "Species Interactions and Competition," *Nature Education Knowledge,* vol. 4, p. 8, 2013.

[19] R. Krone, L. Gutow, T. Brey, J. Dannheim, and A. Schröder, "Mobile demersal megafauna at artificial structures in the German Bight – Likely effects of offshore wind farm development," *Estuarine, Coastal and Shelf Science,* vol. 125, pp. 1-9, 2013.

[20] P. D. Causon and A. B. Gill, "Linking ecosystem services with epibenthic biodiversity change following installation of offshore wind farms," *Environmental Science and Policy,* vol. 89, pp. 340-347, 2018, doi: 10.1016/J.ENVSCI.2018.08.013.

[21] J. Dannheim *et al.*, "Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research," *ICES Journal of Marine Science,* vol. 77, pp. 1092-1108, 2020.

[22] A. B. Gill, M. Bartlett, and F. Thomsen, "Potential interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments," *Journal of Fish Biology,* vol. 81, pp. 664-695, 2012, doi: 10.1111/j.1095-8649.2012.03374.x.

[23] A. Abramic, A. G. Mendoza, and R. Haroun, "Introducing offshore wind energy in the sea space: Canary Islands case study developed under Maritime Spatial Planning principles," *Renewable and Sustainable Energy Reviews,* vol. 145, 2021.

[24] Joint Nature Conservation Committee, "Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise," 2010.

[25] A. M. Fowler, A. M. Jørgensen, J. C. Svendsen, P. I. Macreadie, D. O. B. Jones, and A. R. Boon, "Environmental benefits of leaving offshore infrastructure in the ocean," *Frontiers in Ecology and the Environment,* vol. 16, pp. 571-578, 2018.

[26] G. Nehls, A. J. P. Harwood, and M. R. Perrow, "Marine mammals," in *Wildlife and Wind Farms, Conflicts and Solutions. Offshore: Potential Effects*, M. Perrow Ed.: Pelagic Publishing, 2019.

[27] W. T. Ellison, B. L. Southall, C. W. Clark, and A. S. Frankel, "A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds," *Conservation Biology,* vol. 26, pp. 21-28, 2012, doi: 10.1111/j.1523-1739.2011.01803.x.

[28] L. Hatch and K. Fristrup, "No barrier at the boundaries: implementing regional frameworks for noise management in protected natural areas," *Marine Ecology Progress Series,* vol. 395, pp. 223-244, 2009.

[29] Scottish Natural Heritage, "Dealing with construction and birds: Guidance," 2016.

[30] A. T. Marques, H. Batalha, S. Rodrigues, H. Costa, M. J. R. Pereira, and C. Fonseca, "Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies," *Biological Conservation,* vol. 179, pp. 40-52, 2014.

[31] V. L. G. Todd, L. Lazar, L. D. Williamson, I. T. Peters, A. L. Hoover, and S. E. Cox, "Underwater Visual Records of Marine Megafauna Around Offshore Anthropogenic Structures," *Frontiers in Marine Science,* vol. 7, p. 230, 2020.

[32] O. Langhammer, "Artificial reef effect in relation to offshore renewable energy conversion: State of the art," *The Scientific World Journal,* vol. 2012, pp. 1-8, 2012, doi: 10.1100/2012/386713.

[33] F. Thomsen and T. Verfuss, "Mitigating the effects of noise," in *Wildlife and Wind Farms, Conflicts and Solutions. Offshore: Monitoring and Mitigation*, M. Perrow Ed.: Pelagic Publishing, 2019.

[34] J. Dannheim, S. Degraer, M. Elliot, and K. Smyth, "Seabed communities," in *Wildlife and Wind Farms, Conflicts and Solutions. Offshore: Potential Effects*, M. Perrow Ed.: Pelagic Publishing, 2019.

[35] E. A. S. Linley, T. A. Wilding, K. Black, A. J. S. Hawkins, and S. Mangi, "Review of the reef effects of offshore wind farm structures and potential for enhancement and mitigation," 2007.

[36] S. Perkol-Finkel and Y. Benayahu, "Differential recruitment of benthic communities on neighboring artificial and natural reefs," *Journal of Experimental Marine Biology and Ecology,* vol. 340, pp. 25-39, 2007, doi: 10.1016/j.jembe.2006.08.008.

[37] P. Andersen, M. Borup, and T. Krogh, "Managing long-term environmental aspects of wind turbines: A prospective case study," *International Journal of Technology, Policy and Management,* vol. 7, pp. 339-354, 2007.

[38] D. C. Invernizzi, G. Locatelli, A. Velenturf, P. E. D. Love, P. Purnell, and N. J. Brookes, "Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning," *Energy Policy,* vol. 144, p. 111677, 2020.

[39] J. Petersen and T. Malm, "Offshore Windmill Farms: Threats to or Possibilities for the Marine Environment," *AMBIO A Journal of the Human Environment,* vol. 35, pp. 75-80, 2006.

[40] M. Glarou, M. Zrust, and J. C. Svendsen, "Using Artificial-Reef Knowledge to Enhance the Ecological Function of Offshore Wind Turbine Foundations: Implications for Fish Abundance and Diversity," *Journal of Marine Science and Engineering,* vol. 8, p. 332, 2020.

[41] M. Elliott, D. Burdon, K. L. Hemingway, and S. E. Apitz, "Estuarine, coastal and marine ecosystem restoration: Confusing management and science – A revision of concepts," *Estuarine, Coastal and Shelf Science,* vol. 74, pp. 349-366, 2007, doi: 10.1016/J.ECSS.2007.05.034.

[42] R. Windemer and R. Cowell, "Are the impacts of wind energy reversible? Critically reviewing the research literature, the governance challenges and presenting an agenda for social science," *Energy Research & Social Science,* vol. 79, p. 102162, 2021, doi: https://doi.org/10.1016/j.erss.2021.102162.

[43] R. Inger, M. J. Attrill, S. Bearhop, A. C. Broderick, W. J. Grecian, and D. J. Hodgson, "Marine renewable energy: potential benefits to biodiversity? An urgent call for research," *Journal of Applied Ecology,* vol. 46, pp. 1145-1153, 2009.

[44] K. Smyth, N. Christie, D. Burdon, J. P. Atkins, R. Barnes, and M. Elliott, "Renewables-to-reefs: Decommissioning options for the offshore wind power industry," *Marine Pollution Bulletin,* vol. 90, pp. 247-258, 2015, doi: 10.1016/J.MARPOLBUL.2014.10.045.

[45] O. Langhamer and D. Wilhelmsson, "Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes - A field experiment," *Marine Environmental Research,* vol. 68, pp. 151-157, 2009, doi: 10.1016/j.marenvres.2009.06.003.

[46] J. C. Wilson and M. Elliott, "The habitat-creation potential of offshore wind farms," *Wind Energy,* vol. 12, pp. 203-212, 2009, doi: 10.1002/we.324.

[47] D. J. Sheehy and S. F. Vik, "The role of constructed reefs in non-indigenous species introductions and range expansions," *Ecological Engineering,* vol. 36, pp. 1-11, 2010.

[48] L. F. Gușatu, S. Menegon, D. Depellegrin, C. Zuidema, A. Faaij, and C. Yamu, "Spatial and temporal analysis of cumulative environmental effects of offshore wind farms in the North Sea basin," *Scientific Reports,* vol. 11, p. 10125, 2021.

[49] B. Broström, E. Ludewig, A. Schneehorst, and T. Pohlmann, "Atmosphere and ocean dynamics," in *Wildlife and Wind Farms, Conflicts and Solutions. Offshore: Potential Effects*, M. Perrow Ed.: Pelagic Publishing, 2019.

[50] M. R. Perrow, "A synthesis of effects and impacts," in *Wildlife and Wind Farms, Conflicts and Solutions. Offshore: Potential Effects*, M. Perrow Ed.: Pelagic Publishing, 2019.

[51] E. Masden, A. McCluskie, E. Oewn, and R. H. W. Langston, "Renewable energy developments in an uncertain world: The case of offshore wind and birds in the UK," *Marine Policy,* vol. 51, pp. 169-172, 2015.

[52] Renewable UK, "Cumulative Impact Assessment Guidelines Guiding Principles For Cumulative Impacts Assessment In Offshore Wind Farms," 2013.

[53] Zero Waste Europe. "A Zero Waste hierarchy for Europe." https://zerowasteeurope.eu/2019/05/a-zero-waste-hierarchy-for-europe/ (accessed 09/07/2021.

[54] Zero Waste International Alliance. "Zero Waste Hierarchy of Highest and Best Use." https://zwia.org/zwh/ (accessed 09/07/2021.

[55] E. Topham, D. McMillan, S. Bradley, and E. Hart, "Recycling offshore wind farms at decommissioning stage," *Energy Policy,* vol. 129, pp. 698-709, 2019.

[56] C. Birkland, "Assessing the Life Cycle Environmental Impacts of Offshore Wind Power Generation and Power Transmission in the North Sea," Norwegian University of Science and Technology Department of Energy and Process Engineering, 2011.

[57] E. Topham, E. Gonzalez, D. McMillan, and E. João, "Challenges of decommissioning offshore wind farms: Overview of the European experience," *Journal of Physics: Conference Series,* vol. 1222, 2019.

[58] Arup, "Cost Estimation and Liabilities in Decommissioning Offshore Wind Installations Public Report," 2018.

[59] A. C. Vaissière, H. Levrel, S. Pioch, and A. Carlier, "Biodiversity offsets for offshore wind farm projects: The current situation in Europe," *Marine Policy,* vol. 48, pp. 172-183, 2014.

[60] M. C. Ashley, S. C. Mangi, and L. D. Rodwell, "The potential of offshore windfarms to act as marine protected areas - A systematic review of current evidence," *Marine Policy,* vol. 45, pp. 301-309, 2014, doi: 10.1016/j.marpol.2013.09.002.

[61] S. Gourvenec, F. Sturt, E. Reid, and F. Trigos, "Global assessment of historical, current and forecast ocean energy infrastructure: Implications for marine space planning, sustainable design and end-of-engineered-life management," *Renewable and Sustainable Energy Reviews,* vol. 154, p. 111794, 2022, doi: https://doi.org/10.1016/j.rser.2021.111794.

[62] A. Jadali, A. Ioannou, and A. Kolios, "A multi-attribute review toward effective planning of end-of-life strategies for offshore wind farms," *Energy Sources, Part B: Economics, Planning, and Policy,* vol. 16, no. 6, pp. 584-602, 2021, doi: https://doi.org/10.1080/15567249.2021.1941434.

[63] A. Velenturf, "A Framework and Baseline for the Integration of a Sustainable Circular Economy in Offshore Wind," *Energies,* vol. 14, no. 17, p. 5540, 2021, doi: https://doi.org/10.3390/en14175540.

[64] E. L. Delaney *et al.*, "An integrated geospatial approach for repurposing wind turbine blades," *Resources, Conservation and Recycling,* vol. 170, p. 105601, 2021, doi: https://doi.org/10.1016/j.resconrec.2021.105601.

[65] Department for Business Energy and Industrial Strategy, "Decommissioning of Offshore Renewable Energy Installations under the Energy Act 2004: Guidance notes for industry," 2019.

[66] B. Snyder and M. J. Kaiser, "Offshore wind power in the US: Regulatory issues and models for regulation," *Energy Policy,* vol. 37, pp. 4442-4453, 2009.