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Towards holistic, participative and adaptable governance for offshore wind farm decommissioning

Lobke H. Jurrius *, Luc van Hoof

Wageningen Marine Research, IJmuiden, the Netherlands

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ABSTRACT

The earliest generation of offshore wind farms across Europe soon approach their end-of-life phase. Recent academic and societal attention has centred on the 'artificial reef effects' of offshore wind farms, triggering concerns regarding how to appropriately approach the decommissioning of the monopiles. Wind turbines and their foundations are jurisdictionally expected to be fully removed. Partial decommissioning, in which structures are left in place, is raised as a potential alternative that is anticipated to have ecological benefits over full decommissioning. Despite a strong growing scientific interest in OWF decommissioning, as well as an increasing public debate on the issue, a comprehensive approach to decommissioning decision-making has not yet landed in the actual regulatory processes. This gap is strikingly apparent in the Netherlands, where two OWFs will be decommissioned in the coming years. This paper explores where stakeholders believe the current bottlenecks exist, and how progress can be made towards decisive but inclusive decision-making. Based on individual co-creation sessions with concerned stakeholders, it offers multiple recommendations, including broadly supported criteria to be considered when comparing decommissioning alternatives, as well as underlying perceptions or patterns to be recognised, such as liability concerns, ecosystem valuation, lock-in and path dependency. The discussions and conclusions from this paper can be applied in all countries where decommissioning of OWFs is imminent, and thereby be used as a guide towards inclusive, adaptive and holistic governance within marine management.

1. Introduction

In order to reduce carbon emissions, EU countries are rapidly investing in offshore renewable sources, including offshore wind power. A steadily increasing number of gigawatts (GW) is added annually, which has led to a cumulative offshore wind capacity of over 30 GW by 2023 [90]. The EU Strategy on Offshore Renewable Energy aims for 60 GW of energy produced from offshore wind farms (OWFs) by 2030, rising to 300 GW by 2050, underpinning the EU's ambition to reach carbon neutrality by 2050 [21]. Interestingly, however, while offshore wind is still in the midst of development and rapid scale-up, the decommissioning phase (i.e. dismantling and disposal) is already fast approaching for the first OWFs throughout Europe. The way these earliest turbines were designed results in their profitability being minimised after 20–30 years of operation [62,81]. Although repowering (i.e. reusing the foundations for new turbines) could be considered [37,83], this alternative appears impractical for the first-generation OWFs due to technical limitations and the larger size of modern turbines [80].

Moreover, both the soft-law guidelines in the IMO Resolution A.672 (IMO Guidelines) as well as binding legal obligations from United Nations Convention on the Law of the Sea (UNCLOS) Article 60(3) call for the entire removal of installations that are placed onto the seabed [75]. Also, the OSPAR Commission's Decision 98/3 states that in case artificial structures have not purposely been designed and built as 'artificial reefs', these are bound to complete removal, only allowing for very few technical exceptions [63]. Specifically, Decision 98/3 (p. 16) states that "*the dumping, and the leaving wholly or partly in place, of disused offshore installations within the maritime area is prohibited.*". There are also specific decommissioning commitments at the national level. In the Netherlands, for example, limited agreements are in place on decommissioning at the end of the OWF's lifetime. The site must be left in an equal state after use, and at least eight weeks before decommissioning, the owner (usually a consortium of companies) submits a decommissioning plan to the Dutch government [39,73].

Therefore, complete decommissioning of all structures of these OWFs appears inevitable, which involves 'returning a site [as] close to its

* Corresponding author.
E-mail address: lobke.jurrius@wur.nl (L.H. Jurrius).

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original state as is reasonably possible' [83]. The act of decommissioning is not only expected to involve complex technological activities and economic investments, it will also inevitably cause effects on the local habitats and species communities that have formed surrounding these structures [27,75]. The substantial increase in decommissioning of offshore energy structures has already been indicated as an emerging global biological conservation issue [77]. Partly due to emerging scientific and societal attention for the potential favourable effects of OWFs (artificial reef effects and protection potential for other anthropogenic (bottom-disturbing) activities), the debate on OWF decommissioning is gradually heating up, questioning whether complete decommissioning provides the best course of action. Moreover, the question arises as to what is effectively meant by restoring the site to its *original* state.

Various alternatives to full decommissioning of OWF can be envisaged, ranging from several options of partial decommissioning (varying in the metres above seabed level the foundations are cut off), leaving only scour protection[1] behind, repurposing of the foundations, or artificial reefing of the decommissioned material [27,37,83]. 'Partial decommissioning' therefore includes all alternatives where a larger part of the construction is left behind, than in the currently anticipated method where the monopiles are cut several meters below the seabed level. Leaving structures partially in place may present several environmental (preservation of novel formed habitats and ecosystems), technological (safer removal procedures) and economic opportunities (less complex and hence more cost-efficient procedures) [12,27,34,47,65,81,83]. On the other hand, partial decommissioning may raise navigational and safety issues and hence risks of liability (Article 60(3) of UNCLOS) and may inhibit future exploitation of these areas by other users, such as fisheries. Moreover, in the case costs are reduced when opting for a technologically easier-to-implement strategy -which can be expected to be the case of partial decommissioning- greenwashing concerns may arise, as such discourse seemingly dominated the similar decommissioning debate for the Oil and Gas (O&G) industry [26].

The controversy surrounding how to approach offshore decommissioning is not new and certainly not uncharted territory. In the 1990s, Shell's Brent Spar oil-platform in the North Sea became redundant. The UK government gave Shell the license to dispose of the platform in the Deep Water [4,42,53]. Shell UK complied fully with British requirements for decommissioning and, additionally, complied with the international guidelines and UK practice in conducting a Best Practicable Environmental Option study [72]. Disposal at sea was deemed safe and cost-effective compared to dismantling on land, which was riskier for potential spills and four times more expensive [17,42]. Despite Shell's compliance with all regulations, Greenpeace opposed the sea disposal, citing environmental concerns. Following a comprehensive policy review, it was decided in 1998 to repurpose the platform by cutting it into sections to be used for a quay extension in Norway [42]. The Brent Spar case thereby set the stage for future discussions about decommissioning offshore structures. With regard to O&G, efforts have been made to liberalise the current jurisdictional decommissioning obligations and provide leeway to alternative decommissioning options [43]. Ironically, however, these attempts have only resulted in even stricter OSPAR policies, namely excluding 'all non-virgin materials as acceptable reef construction materials' [43].

Yet the emerging era of OWF decommissioning seems to have reopened the debate and again sparked calls for an integrated assessment of how to approach this activity. From the growing body of literature, it again becomes evident that the issue of decommissioning is a multifaceted challenge in which the exact nature of the problem and potential solutions are perceived differently by different stakeholders [46,57]. Scholars have called for including ecological criteria in OWF decommissioning decision-making [27] and emphasised that the decommissioning phase should be part and parcel of the OWF Environmental Impact Assessments (EIA), to structurally assess the best applicable approach [34,75]. Furthermore, to avoid unbalanced decision-making, stakeholder participation should be an indispensable part of these decommissioning decision-making processes [26,28,46,75]. It is evident that the roles and responsibilities of stakeholders directly and indirectly involved are currently not set but are in flux. While this aligns with the current rapid developments in the OWF field, which theoretically makes it possible to adjust the rules along the process of implementation, it also generates unclarity and inertia among the stakeholders. However, it has been highlighted that currently there is either insufficient or ineffective stakeholder engagement in the OWF decommissioning decision-making process [26,28,46].

However, while the demand for more integrated and inclusive decision-making seems to increase, a lack of coordinated efforts to decisively transform existing know-how into articulated decision-making processes persists. This study responds to this observation that, on the one hand, the focus on the decommissioning of OWFs is intensifying, fuelling the demand for holistic decision-making, and, on the other hand, policy seems to be stagnant and does not allow room for this integral assessment and participative decision-making. By building on concepts related to integrated, participatory and adaptive marine governance, it explores how these can be integrated with the discourse on decommissioning OWFs. By actively involving stakeholders, their views, needs, perceived constraints and interests are explored. Through both analytical and empirical focus, it presents a set of recommendations regarding current barriers and stakeholder concerns hopefully facilitating the transition from the academic debate to actual policy responses.

It thereby focuses on the case of the Netherlands. In the Netherlands, two OWFs are rapidly approaching their end-of-life phase: Offshore Windfarm Egmond Aan Zee (OWEZ, 36 turbines in 27 km^2, 108 MW and Prinses Amalia Wind Park (PAWP, 60 turbines in 14 km^2, 120 MW) (Fig. 1). OWEZ is operational since 2007 and has to be decommissioned by 2027. With 108 MW (3 MW per turbine) for OWEZ and 120 MW (2 MW per turbine) for PAWP these OWFs have relatively small capacity compared to current OWFs in development or recently commissioned (e.g. 1400 MW for Hollandse Kust West and 4000 MW for OWF IJmuiden Ver). PAWP is operational since 2008 and has to be decommissioned by 2028 [61]. In the Netherlands, OWF permits explicitly state the obligation to remove all structures, for which a cutting level of 6 m below the seabed is expected [78].

Chapter two briefly discusses the methodology, after which the findings are presented in four chapters. Chapter three presents the complexity of the theoretical governance landscape in which OWF decommissioning is found (the '*Why*'). Chapter four presents the OWF landscape of the Netherlands (the '*Who*'). Chapter five presents and discusses the various considerations in decommissioning decision-making as proposed by stakeholders (the '*What*'). Chapter six suggests governance measures taken to enable inclusive and holistic decision-making on decommissioning (the '*How*'), after which Chapter seven presents the main conclusions.

2. Methodology

As aforementioned, this study contains an analytical and empirical approach, namely through literature review and stakeholder engagement respectively. First, through a literature review, the governance structures behind decommissioning issues were explored. Thereafter, 19 (due to Covid-19 online) 1-on-1 sessions were held with 19 stakeholders involved in OWF decommissioning in the Netherlands. Stakeholders

[1] The presence of a monopile in a marine environment changes the flow pattern in its immediate area, resulting in increased local sediment transport. This causes scouring of the seabed around the monopile—a serious risk that may compromise the stability of the wind turbine foundation. In addition, the cables on the seabed may risk exposure due to the eroded seabed around the monopile. Materials, usually boulders, are placed around the base of the monopile on the seafloor to prevent this soil erosion (DHI, 2024, website)

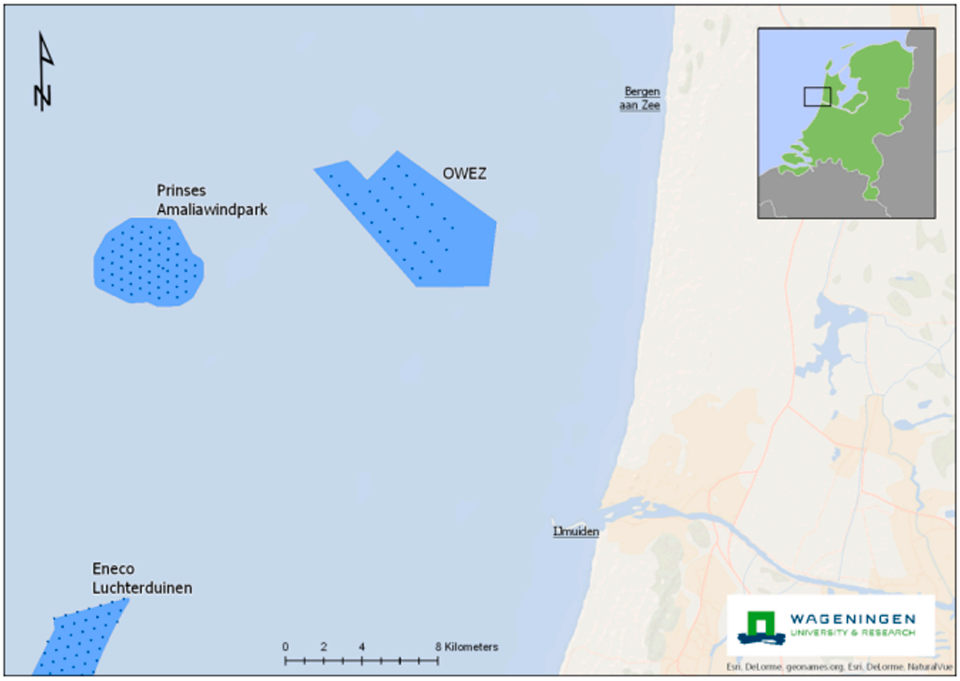

Fig. 1. The locations of offshore wind farms PAWP and OWEZ [31].

were selected based on their professional stake in offshore wind decommissioning or having scientific expertise in this field. Stakeholders included marine environmental consultants (2), marine ecologist (1) environmental non-governmental organisation (eNGO) representatives (3), OWF operators (2), offshore contractors (3, of which one has provided input through email), governmental organisations/civil servants (3), offshore wind sector association representative (1), offshore recreational sector representative (1), fishing industry representative (1) and Oil and Gas (O&G) sector representative (1) from the Netherlands.

During these sessions, several inputs were collected across three themes: 1) How stakeholders regarded the current decommissioning debate in the Netherlands, 2) What stakeholders deemed technologically feasible decommissioning options (irrespective of their legal potential), and 3) What economic, environmental and social criteria stakeholders deemed as crucial and valuable criteria to consider when evaluating these decommissioning options. The latter input was gathered by guiding the respective stakeholders through an extensive synthesis of criteria on which decommissioning alternatives can be evaluated. This initial list was based on considerations mentioned in [45,46] and [75] for OWFs, and [29,36] and [76] for O&G. It resulted in a list of 54 criteria that were either already applied to evaluate decommissioning alternatives or had been proposed to be applied. The stakeholder was subsequently invited to select which criteria he/she considered most and least critical and valuable in evaluating decommissioning alternatives and invited to elaborate on why this was the case. These inputs were recorded and synthesised. The output was anonymised. The results have been presented along four dimensions: the Why (Governance dynamics in OWF decommissioning), the Who (OWF decommissioning stakeholder landscape in the Netherlands), the What (Proposed considerations in OWF decommissioning decision-making) and the How (Recommendations towards adaptive and participative consideration of decommissioning alternatives).

3. The WHY: Governance dynamics in OWF decommissioning

Following [86], the playing field and governance of OWF decommissioning can be defined as the combination of structures, rules and processes, how they are set up and changed, by whom they are implemented, how others are involved, and whom they affect, both in written as well as unwritten rules. In OWF decommissioning management, it thus poses the question of who is involved, which problems are addressed, who is going to address these problems and who can or should participate in these processes. To analyse this complex and challenging nature of the debate on decommissioning OWFs, this section explores its governance dynamics, involving its *locked-in* and *path-dependent* nature, requiring *adaptive* and *participatory* solutions.

Firstly, it is important to recognise that OWF decommissioning takes place within a rapidly evolving marine socio-ecological system that is characterised by continuous change, associated with uncertainty and unpredictability [79]. Governance of marine systems therefore unavoidably needs to consider 'moving baselines' of social and ecological developments, including climate change and marine exploitation [18,79]. Today's best decommissioning method may be obsolete in a few years, depending on technological inventions, developments in societal attitudes and ecological findings. This requires flexibility in marine management to accommodate moving baselines. However, such desired flexibility is primarily lacking in processes that are path-dependent and 'locked-in' [44,58].

Path dependency results from established infrastructure, economic interests, existing legislation and societal expectations, making a transition to more sustainable alternatives challenging [44] and possibly resulting in sub-optimal outcomes [59]. In the case of our field of study, the decommissioning of OWFs is governed by similar, if not identical, regulations and laws as for the O&G industry, including international and national regulatory frameworks [57]. Also, expectations for the decommissioning approach of OWF in the current experience-poor climate are mainly based on experiences from the O&G industry [50,74,82]. Although the general idea of OWF construction and decommissioning is comparable to that of O&G, the two arenas differ enough to ask for different approaches to their marine management issues [75]. For example, the construction of OWFs involves a more widespread surface area with multiple structures in shallower waters, while O&G often involves a single platform in deeper waters [75].

Moreover, a 'lock-in' occurs when a particular management strategy becomes dominant (often due to path dependency), and involves a situation in which established regulations or technological developments are formed as 'status quo', making it difficult for alternatives to gain traction [44]. The current rigid commitment to full decommissioning precludes an adaptive approach, where newer and more efficient technologies can be integrated into the decommissioning process as soon as they emerge. Moreover, with a generic approach, it becomes impossible to take into account unique ecosystems and environmental sensitivities as soon as these were to be discovered. The established formal and written regulatory frameworks are currently resistant to change due to bureaucratic inertia or a lack of adaptability.

Overcoming path dependency and lock-in in socio-ecological systems requires the adoption of transdisciplinary, adaptive, experimental and participative approaches to marine governance [44,58] This includes overarching silos, enabling adequate stakeholder participation, addressing complexity and expose conflicting economic and conservation priorities [44]. However, while adopting such transformative governance approaches, further path dependencies and consequent lock-ins must be avoided. Therefore, adaptivity in management and decision-making is important, which emphasises flexibility in dynamic, interconnected and uncertain systems through continuous learning and reflection. Adapting and evolving governance processes support navigating through complexity (e.g. strategies, policy and practices) by being responsive to feedback and new information from continuous socio-ecological developments [15,24] Adaptive governance, a process in which there is an evolution of the rules and norms based on decentralised decision-making structures seeking to inform higher-level decisions from bottom-up [7,35], further embeds principles as transformative experimentation, e.g. pilot project implementation, to test and evaluate potential solutions to governance challenges [24,44] and stakeholder involvement and participation [15,24,79].

Stakeholder participation in decision-making in policy making or in research, underlying participative governance, can manifest in various ways and degrees, and serve different objectives [19]. Participative approaches include joint knowledge production, sustainable dialogue and improvement of the legitimacy of management and decision-making processes [49]. Stakeholders can further be included in different phases in governance processes, ranging from communication towards stakeholders, to providing authority to these parties in decision-making [60]. Transparency by policymakers, especially regarding the space available for innovative governance processes, and effective expectation management among actors are considered crucial for successful participation [60]. It should go beyond involving academia [57,6]. Simultaneously, this requires careful consideration of 'ticking the box' stakeholder input, avoiding stakeholder fatigue and power imbalances between stakeholders [29].

In summary, OWF decommissioning is an intersectoral and interdisciplinary challenge in marine governance against the background of the aforementioned 'moving baseline', prevailing unknowns and diverse range of stakes involved. Reflecting on the decommissioning of OWF, with its newness and uncertainty, the many deliberations involved, the number of stakeholders concerned and its existence within a marine ecosystem that is not yet fully comprehended, it is clearly a 'wicked problem'. Wicked problems are defined as societal challenges of which the diverse, complex and dynamic nature lead to a seemingly no-win situation and it is not clear when and how they are solved [40]. Wicked problems are characterised by difficulties in definition, uncertainty, and conflicting perspectives and values. Furthermore, [40] state that "wicked problems are often symptoms of larger issues", indicating the multi-layered dimension of these challenges. Wicked problems may have no technical quick fix and have no right or wrong governance solution that can be determined scientifically [40]. In order to address wicked problems, governance must rely on the collective judgment of stakeholders involved in a process that is both experiential, interactive and deliberative [40].

4. The WHO: OWF decommissioning stakeholder landscape in the Netherlands

In the Netherlands four main stakeholder groups were identified that participate in the OWF decommissioning debate: the regulatory enabling environment, the offshore wind industry, and other North Sea users, including nature (groups involved with environmental advocacy, consultancy and science) (Fig. 2). This paper deliberately refers to 'stakeholders' rather than 'actors', defining *stakeholders* as being affected by, or have the power to affect, decision-making, while *actors* are considered to constitute all parties or individuals present within a system of interest (i.e. all actors present in the chosen marine environment) [55,67], though both are often used interchangeably in literature [24,60,69].

The *Regulatory environment* develops and enforces policies and regulations related to offshore decommissioning. Government agencies such as Rijkswaterstaat (Department of Waterways and Public Works) and RVO (Netherlands Enterprise Agency) ensure the enforcement and licensing of policies and regulations set by Dutch ministries, for example, licensing and environmental impact assessment requirements for OWF construction and decommissioning. The *Regulatory environment* therefore influences the *Wind industry* (License holders, Operators, and Contractors) through its decision-making. License (i.e. permit) holders are granted temporary access to exploit activities at a certain site for a certain period. Operators operate the OWF once it is commissioned. In the Netherlands, it is common that the permit holder and operator are the same entity. Contractors are involved in the actual construction and decommissioning of an OWF. Commonly, a multitude of contracting parties are involved throughout the lifetime of an OWF.

The decommissioning of OWFs impacts several other stakeholders outside the Regulatory and Wind energy environment, including shipping, recreation, fisheries, O&G industry, the military and sand extraction. This includes restricted access or navigational hindrance, safety risks (damage, capsising) or loss of exploitation grounds [26]. The marine ecological environment is also affected and therefore considered a stakeholder, for which independent knowledge from scientists and other knowledge institutes (e.g. environmental advisory bodies) on environmental opportunities and risks of decommissioning can be included, as well as viewpoints expressed by eNGOs.

The stakeholder sessions show that both regulatory ambiguity and divergent expectations regarding prospective decommissioning exist among stakeholders, and resulting uncertainties, hamper concrete planning actions. For example, the perceived expected level of removal of the monopile varies between operators and contractors (varying from 2 to 5 m below the seabed level) and uncertainties exist regarding the expected cost and existing technological capabilities for removal. Although the subject of decommissioning is increasingly being discussed in the industry and the decommissioning of the first OWF is eminent, it was often still considered premature or precarious to take decisive action according to the industry stakeholders. Meanwhile, the fishing industry expresses the expectation that the area will be fully decommissioned and reopened.

5. The WHAT: Proposed considerations in OWF decommissioning decision-making

Having briefly examined *'who'* has a stake in the decommissioning debate, the next step is to explore *'what'* to consider when comparing decommissioning alternatives. This section assesses what, according to the stakeholders, are the key considerations to be taken into account in the decision-making process and discusses these considerations briefly drawing on existing literature. Several studies already embarked upon the journey to evaluate appropriate and imperative criteria to be factored into OWF decommissioning decision-making [27,46,75,83]. Also for O&G, where decommissioning has become a common and established practice, studies on decommissioning criteria are available

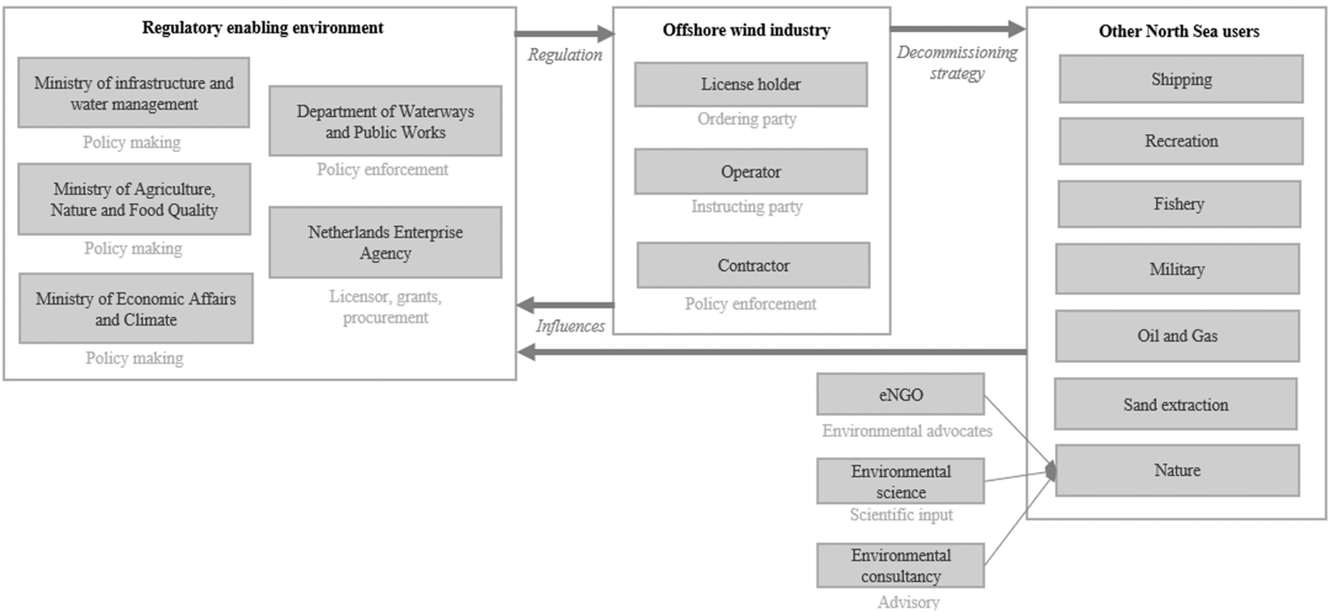

Fig. 2. Key stakeholder landscape for OWF decommissioning in the Netherlands (source: this study).

[27,36,76].

A longlist of criteria from these existing studies was discussed during the individual stakeholder sessions, as explained in Section 2. This resulted in a shortlist of ten criteria that received the most acclaim across stakeholders. This list thereby presents a first outline of the issues that stakeholders in the Netherlands consider important to include when holistically assessing OWF decommissioning alternatives: biodiversity change, nature protection potential, habitat alteration, decommissioning costs, opportunity costs to fisheries, material recycling benefits, liability costs, ocean access, recreational opportunities and political compatibility. The definition of each of these criteria, as presented to stakeholders, is provided in Table 1. Although it was expected that 'technical feasibility' would be considered a primary factor in how to approach the decommissioning of OWFs, the technical complexity of the process is fully reflected in the decommissioning costs according to industry stakeholders. Hence, considering technical feasibility separately was eventually deemed unnecessary. The next sections will provide insight into the stakeholders' motivations regarding these criteria, alongside relevant literature found.

5.1. Environmental criteria: Biodiversity change, protection potential and habitat alteration

The rapid development of OWFs implies a tremendous amount of artificial structures being added to European waters and inherently changes the marine ecosystem [8]. Extensive research has already been conducted on the manner and extent of environmental impact that artificial structures, including OWFs, have on marine ecosystems [5,52]. This involves the effects on benthic communities [12,13,51], fish [68], seabirds [56,87], marine mammals [33,88], spread of invasive species [11,12,14,27] as well as more comprehensive research on cumulative effects [32] and ecosystem functioning and services [12,8]. Two potential environmental benefits of OWFs mostly referred to within the decommissioning debate are 'artificial reef effects' and their potential role as 'indirect marine protected areas'. By adding hard substrate to previously predominantly soft-sediment habitats, marine life across multiple food web levels is attracted for settling, spawning, foraging and refuging, leading to increases in biodiversity, also referred to as 'artificial reef effects' [10,26,51,6,78]. Furthermore, bottom-disturbing activities such as bottom trawl-fishing are commonly prohibited in OWFs [85], hence OWFs are occasionally referred to as 'marine nature nurseries' or sometimes even as 'indirect marine protected areas (MPAs) [3].

Practical experience and complementary scientific evidence to substantiate how these environmental impacts of OWFs (positive and negative) may reverse once they are decommissioned are however currently extremely scarce [50]. Complete removal of monopiles introduces temporary environmental impacts, e.g. through carbon emissions [38] and seabed disturbance during operations [27], but also effects that are long-term or occur elsewhere in the value chain [48]. For example, recovery to pre-OWF conditions could at least take decades, as is described for O&G [71], or may not be possible at all as recovery rates of benthic communities tend to depend on the spatial scale, duration and frequency of the disturbance [75]. Furthermore, considering the decommissioned area will be opened for other sea users after 'returning to pre-OWF' conditions, bottom trawling and other operations that may affect the marine environment in this area may again resume. Given this diversity of environmental impacts (direct and indirect, widespread and local, short- and long-term), informed decision-making and minimisation of negative environmental impacts requires an integrative environmental analysis of decommissioning alternatives.

However, the stakeholder sessions exposed a more fundamental governance issue underlying this environmental analysis. Both an unclear definition of the specific kind of nature desired in the North Sea and a divergent perception of the actual value of settled ecosystems in OWFs play a role in stakeholders' reserved attitude towards partial decommissioning. Whilst some advocate in favour of considering the net environmental benefits as a reason for leaving structures behind, stakeholders therefore gave varying responses to these potential advantages. On the one hand, the structural loss of biogenic reefs in the North Sea was referred to, for which abandoned structures could provide restoration opportunities, as no bottom-fishing will be able to take place here. The eNGO representatives that were involved in the study, on the other hand, emphasised the 'unnatural' nature of these structures and that this should not be forgotten in the discourse to enhance biodiversity beyond reason. Given that none of the used materials were initially present in the North Sea ecosystem, restoration of the state of the environment pre-OWF should remain the guiding objective to avoid unnecessary pollution of the environment and to prevent the emergence of 'artificial reefs of convenience'. This includes scour protection, despite having a more natural character according to various stakeholders, and therefore possibly receiving more policy support than

Table 1
Short-list of criteria for stakeholders in the Netherlands (source: this study).

Dimension	Criteria	Definition
Environmental	Change in biodiversity	The expected level of biodiversity (i.e. species richness) after successful implementation of the proposed strategy, compared to the baseline strategy (cutting below the seabed)
	Nature protection potential	The area is protected from anthropogenic disturbance of habitat with conservation objectives after the successful implementation of the proposed strategy.
	Habitat alteration	The expected degree of change in geomorphological characteristics of the benthic zone due to executing the proposed strategy compared to the baseline strategy (cutting below the seabed)
Economic	Decommissioning cost	Estimated costs of the decommissioning process that have to be spent by the operator to successfully execute the proposed strategy, compared to baseline strategy (cutting below the seabed).
	Opportunity costs for fisheries	An estimate of the financial gain or loss of commercial trawl-fishing in the decommissioned OWF site after successfully executing the proposed strategy, compared to the baseline strategy (cutting below the seabed).
	Material recycling benefits	Estimated benefits from reusing or recycling the retained material from the monopile after successfully executing the proposed strategy.
	Residual liability costs	Estimated cost-intensity derived from residual liability by the operator including monitoring costs of decommissioned site and safety risks after successfully executing the proposed strategy, compared to baseline strategy (cutting below the seabed)
Social	Ocean access	The expected accessibility of the area by other navigational practices of national importance after successfully executing the proposed strategy, based on the activities of national importance, fisheries and nature conservation.
	Recreational opportunities	The expected opportunities for recreational opportunities within the area after successfully executing the proposed area, including diving, recreational fishing activities and recreational sailing, compared to the baseline strategy (cutting below the seabed).
	Political compatibility	The expected governmental support for the implementation of the proposed strategy, i.e. the suitability of the enabling environment.

abandoning steel structures.

Moreover, the true ‘value’ of these newly established species and ecosystems in OWFs is not yet decided upon, albeit monetary, cultural or inherent worth. Whilst all stakeholders share the view that the ecological value of the area may have elevated in the OWF's operational period, through the exclusion of bottom-disturbing operations and due to artificial reef effects, stakeholders appear indecisive at what point the ecosystems formed within the OWF are ‘valuable enough’ to preserve. Several emphasize that the occurring ecosystem changes may not at all be of the kind sought at the North Sea. Concerns were raised by eNGO representatives that considering post-decommissioned areas as MPAs could even undermine the ambition to conserve other valuable marine habitats in other areas of the North Sea, in case OWFs would also be considered as ‘valuable habitats’ to protect.

5.2. Economic criteria: Decommissioning costs, opportunity costs for fisheries, material recycling benefits and liability costs

Economic criteria relate to assessing the financial feasibility, profitability and economic viability of different alternatives, and provide support in sorting out potential economic costs and benefits of these options [37]. The most intuitive economic criterion is the total cost of decommissioning, which is relevant to the parties executing or contracting the decommissioning. Decommissioning costs involve multiple aspects, amongst others the costs for mobilisation of support vessels, personnel, land-based processing and landfilling [37,81]. At present, economic costs of decommissioning are difficult to predict due to limited available experience, potential changes in laws and regulations, supply chain bottlenecks and lack of reliable data when comparing strategies, and therefore comparison of various strategies is challenging [37]. In case economic benefits are gained by applying alternative decommissioning methods, industry actors can devote saved costs to nature restoration efforts elsewhere to avoid potential greenwashing claims when abandoning structure,. This ensures that savings from ’cheaper’ decommissioning activities should not benefit the operator, but nature restoration actions.

Regarding decommissioning costs, the *‘polluter pays’* principle is deemed prominent in the discourse on decommissioning offshore structures, including O&G [22,41] and OWFs [34,81]. The EU has enshrined this principle, which should incentivise polluters to pay for the pollution they cause, thereby promoting avoidance of environmental damage and increasing accountability (Treaty on the Functioning of the European Union, Article 191(2), [23]. In the field of decommissioning, this entails that the responsibility for all costs of environmental damage, whether from complete decommissioning or leaving structures partially in place, must be borne by the OWF operator or licensee. In this respect, the underlying challenge of the polluter pays principle is the monetary assessment of environmental damage caused. Once again, this points towards the conundrum of how to properly define and approximate the ’valuation’ of nature, as mentioned in Section 4.1.

A criterion that appears on the radar of almost all stakeholders is the anticipated costs of the financial aftercare that would be required after adopting partial decommissioning. These ‘residual liability costs’ include monitoring and maintenance costs, safety measures costs and general liability costs (both for physical damage and personal injury). To the stakeholders, the actual definition of and responsibility for liability seems vaguely defined and unclear, which could hinder their willingness for partial removal. Topham et al. [81] argue that the specification of these liabilities for wind farm owners is recommended to support optimised decommissioning decision-making.

Opportunity costs for fisheries involve an estimate of the financial gain or loss of commercial fishing in the decommissioned OWF site after successfully executing the proposed strategy, compared to the baseline strategy of cutting the monopiles below the seabed level. Also in the case of cutting the monopile below the seabed level, however, navigational safety obligations require that all components of the installation must be cut to an acceptable level and foundations and cables should remain buried [75]. It may be case specific whether under these circumstances commercial fishing can be resumed after decommissioning.

Lastly, decommissioning poses opportunities for material recycling to reduce overall environmental impact [27,34]. The costs for material recycling are considered a relevant criterion among stakeholders. However, the financial benefits of material recycling are dependent on a volatile market for scrap metal, with prices and benefits at the time of decommissioning difficult to predict [37]. To fully unlock the potential of material recycling, logistical and technological developments are required [2,66]. While the benefits of material recycling seemed interesting to the industry in both economic and environmental terms, they expected the decommissioning costs to be significantly higher than the recycling benefits.

Despite the fact that industry players indicated during the stakeholder sessions that they are economically incentivised to leave structures behind as it greatly reduces operational costs, they express concern about liability costs. In case liability responsibilities remain in their hands, or are vaguely defined, industry parties refuse to leave anything at all as it would impose too high risks. Only when no liability remains, for instance by transferring liability to the government, does partial decommissioning become an option for them. However, this option seems unrealistic according to government representatives. It would involve strict nautical safety mitigation measures and significant monitoring and control costs. Albeit expected to have lower risks than O&G, also monopiles should be regularly checked for hazardous and polluting substance risks.

5.3. Social criteria: Ocean access, recreational opportunities, political compatibility

Lastly, social criteria seek to assess the social consequences of various alternatives to ensure that decisions prioritise the well-being of individuals and communities. Safety-related considerations focus on safety both during (offshore personnel safety, and exposure to toxic substances) and after decommissioning (navigational hazards, fishing hazards, access for other sea users). For OWFs, safety issues that arise *after* decommissioning seem to be deemed of higher relevance (e.g. navigational safety), while the opposite is true for O&G, where safety risks *during* decommissioning receive more attention (e.g. exposure to contaminants). The safety of offshore personnel and technical feasibility was not considered crucial by stakeholders, as industry stakeholders argued that these are regarded as preconditions rather than considerations. Public access (also regarded as 'ocean access') was mentioned by all stakeholders except one, demonstrating its importance in decommissioning decisions.

Political compatibility for a decommissioning approach depends on the consistency with the prevailing political environment [75]. At decommissioning, the best available future use will be assessed based on current uses of national importance. One government representative referred to the high value of other maritime activities, and the subordination of nature in that sense, which currently prevents policymakers from designating an area exclusively for nature protection. While several stakeholders mention the potential possibilities for tourism activities (e.g. diving and recreational fishing), this is not considered an activity of national importance. Above all, safety considerations are expected to weigh most heavily in decommissioning policy decisions, signalling deliberations to either remove all structures or to implement strenuous safety mitigation measures, such as buoys or closing the area.

6. The How: Recommendations towards adaptive and participative consideration of decommissioning alternatives

Leaving structures behind can offer opportunities on several levels, including protection from seabed-disturbing activities such as bottom-trawling fisheries and boosting biodiversity and connectivity through blue corridors, yet likewise inherently and inevitably raises challenges for future uses of the area. Though seemingly obvious and rational, considering implications that stakeholders consider fundamental when deciding on approaches to decommissioning, involving stakeholders in their valuation and trade-off analysis is not yet common practice. Fundamental, therefore, is how to organise this in practice. This section proposes five suggestions for approaching the '*how*': 1) Start developing a plan for decommissioning, 2) Integrate stakeholders (expertise and expectations) throughout the decision-making process, 3) Decide on which nature is 'valuable' and 'desired', 4) Look further than decommissioning: define liability costs and responsibilities, and 5) Do not replace a lock-in with a lock-in: case-by-case and learning-by-doing.

6.1. Start developing a plan for decommissioning

Despite the already occasional and upcoming debate, a more structured and decisive discussion is urgently called for, motivated by threefold concerns: 1) currently there is too much uncertainty about what is expected, making it impossible to take any concrete action, 2) the decommissioning is simply close at hand and legislative amendments do not occur overnight, and 3) all stakeholders voice the need of holistic assessments considering the cross-disciplinary nature of decommissioning which takes time.

Firstly, the paradox lies in on the one hand a strict regime for decommissioning, whilst in practice there seems to be a lot of varying interpretations as to what is expected of 'complete decommissioning'. Mostly industry parties expressed that planning the upcoming decommissioning phase appears difficult due to lack in experience and uncertainties in what is expected of them, yet the decommissioning of the two Dutch OWFs is due in respectively three and four years. They expressed concern that policy decisions related to decommissioning were unclearly defined and communicated (e.g. liability issues after decommissioning or the expected depth of cutting below seabed) and therefore hard to anticipate on. But also stakeholders in general showed ranging expectations, for instance whether complete decommissioning would also involve removal of scour protection. Also beyond our case-study, planning decommissioning is considered challenging due to limited prior experiences and poorly defined regulations [1,26,81]. Only starting planning decommissioning during the operational phase may greatly induce costs for wind farm operators [1], especially since financial efforts are often underestimated during the planning phase of OWFs [83]. Also liability issues should be clearly defined to better anticipate the decommissioning phase [81]. In this respect, it is also important to be mindful of whether there are certain unspoken expectations, or so-called unwritten rules, among stakeholders.

Secondly, as scientific consensus on revising laws and regulations already exists [26], should there also be sufficient social demand for the actual application of alternative decommissioning methods, rigid legislation may have to be amended to enable this. Such amendments involve a multi-level and interconnected process, from international (UNCLOS/OSPAR) to EU and national legislation (as discussed in Chapter 1), and is therefore not at all straightforward nor rapidly completed. So while the first OWFs to be decommissioned may already be missing the boat, a timely start to these regulatory development processes is deemed necessary. At this point, such legislative change should still be justified by providing more manoeuvre space to *explore* different decommissioning alternatives, as current assessment of what is the best alternative varies still widely between proponents and opponents, both among academics [26] and among stakeholders in this study.

Lastly, it is considered essential to start with revisiting or creating suitable EIAs on decommissioning practices [34]. The environmental effects of decommissioning strategies, such as reopening the site to fishing and risks to species, should be evaluated before decommissioning starts [27]. As Lemasson et al. [50] further argue, because of the cross-linkages in the intersectoral and interdisciplinary debate, the available knowledge is fragmented among stakeholders. Synthesising and making transparent all available information to inform the debate and subsequent decisions is better to start sooner rather than later. Firing up the debate, starting holistic evaluations and coming to concrete conclusions on the leeway that should, or should not be, provided to alternatives prevents situations such as Brent Spar, or artificial reefs of convenience claims.

6.2. Integrate stakeholders (expertise and expectations) throughout the decision-making process

Stakeholder engagement should be an indispensable part of the multifaceted decommissioning decision-making process. Several studies emphasise the necessity of considering stakeholder input to ensure informed decision-making, enhance societal acceptance of decommissioning strategies, assess ecosystem services impacted by decommissioning and develop metrics for comparability across social, technical, and economic impacts [6,25,27,64,65,89]. Meaningful (e.g. considering power equity issues and ensuring timely involvement) stakeholder participation is essential for gathering insights, perspectives and values regarding OWF decommissioning. This engagement is crucial for identifying issues, such as understanding the ecosystem services gained or lost during decommissioning and developing metrics to quantify these benefits and losses [89]. Ounanian et al. [64] document how differing knowledge frames among stakeholders can lead to conflicts and might hinder collective action. Incorporating stakeholder views into decommissioning decision-making can enable transparent and participatory processes. Stakeholder involvement further contributes to public legitimacy [54]. Facilitating a better understanding of stakeholder values and perceptions is vital for achieving consensus on decommissioning strategies. By engaging stakeholders in discussions about decommissioning options, decision-makers can gain insights into preferences, which may vary based on location, structure type, and scientific evidence or perception [16]. As stated before, doing so requires careful consideration of how stakeholder engagement can be achieved, concerning questions of who should be involved and how to avoid power imbalances.

Several frameworks exist that can help evaluate trade-offs between environmental, societal, and economic impacts in decision-making processes while allowing stakeholder engagement throughout the process and fostering transparency. Social Systems and Ecosystem Assessment frameworks (SSEA), as suggested by Elliott et al. [19], offer a potential avenue for developing metrics that enable quantitative comparisons between decommissioning options. Also, existing tools for ecosystem valuation exist, further exploration is needed to adapt them effectively to decommissioning scenarios [89].

6.3. *Decide on which nature is 'valuable' and 'desired'*

Defining what constitutes valuable nature for protection is crucial for decision-making in decommissioning processes. Despite the pressure on habitats in the North Sea and the potential for hard substrates to restore species that once thrived there, stakeholder sessions revealed a significant debate: what constitutes the desired valuable nature to strive for?

The environmental value of OWFs hinges on the scale of ecosystem benefits they provide [27]. Scour protection can serve as an artificial reef, providing various ecological benefits [30]. However, the impact of changes in biodiversity on ecosystem services remains uncertain [8]. Some argue that changes in seabed ecology due to OWFs are neither inherently positive nor negative but rather different [12]. Stakeholders, however, express concerns that established ecosystems around OWF structures may not warrant conservation efforts and could even detract from protecting other valuable marine habitats in the North Sea when deciding to implement the site as MPA post-decommissioning.

Additionally, increasing biodiversity may not always align with the ecosystem's natural state, and permitting the abandonment of structures as artificial reefs therefore requires caution [85]. The concept of 'artificial reefs for convenience' was mentioned during the stakeholder sessions, referring to leaving structures behind for economic benefits (cost-efficiency advantages arising from reduced technical complex decommissioning practices) yet disguising it with environmental benefits. Moreover, leaving behind the greater breadth of hard structures, including O&G platforms, may lead to undesirable increases in artificial materials in the marine ecosystem. Particularly in relation to the proliferation of other anthropogenic activities inducing impact on North Sea habitat [12], the desirability of such potential development can be called into question. Stakeholders emphasise that artificial structures may provide a 'stepping stone' network across the North Sea habitat which might benefit invasive species. Stakeholders therefore expressed the need for a cautious approach towards leaving structures, voicing concerns regarding this potential precedent effect.

Understanding how OWFs influence ecosystem services requires examining their effects on functional diversity [8]. Considering the interconnectedness of offshore structures and surrounding ecosystems is essential in this evaluation [27] Different approaches, such as no net loss, net positive impact, or relative net environmental benefit, are proposed for defining the environmental impact of decommissioning [27,34].

6.4. *Look further than decommissioning: define liability costs and responsibilities*

Residual liability costs so far appear to be a major driver for full removal for O&G, despite arguments for strong benefits of leaving structures behind [28] and are deemed the most powerful disincentive for abandoning offshore structures [26,71]. The issue of liability for residual risks was labelled as undecided and unclear in the stakeholder sessions, indicating a grey area in marine policy in the Netherlands.

Stakeholders argued that partial decommissioning could reduce financial efforts, yet raised concerns concerning the existing unknowns regarding the actual level of financial effort that will be required. For OWF industry stakeholders, however, the situation was considered 'less burdensome for monitoring and maintenance' and 'less risky for chemicals spills' than in the case of O&G decommissioning. [71] argued for O&G decommissioning, that if adequate and appropriate mitigation measures are implemented (e.g. buoys and updated nautical charts), any incidents are beyond the O&G parties' liability. Also, for OWFs, leaving behind the scour protection was considered less of a risk in terms of residual liability, due to its 'natural and seemingly safe character'.

Even more interestingly, and underpinning the importance of starting up the debate, is that whereas the first Dutch OWFs are up for decommissioning over the next couple of years were single-use operations, for the new generation OWFs in the Netherlands, a greater push for multi-use is noticeable. To be able to sustain all uses and growing needs on the North Sea, the Dutch government emphasises and accommodates the need to move towards a multi-use of space within OWFs, e.g. by passive fisheries, other forms of renewable energy and seaweed cultivation (Noordzeeloket, n.d.). This raises an additional question for decommissioning as in general the economic lifetime of the OWF is shorter than that of its co-located activities [9].

6.5. *Do not replace a lock-in with a lock-in: case-by-case and learning-by-doing*

Decisions on decommissioning options must consider a variety of factors which can vary significantly between offshore structures and evaluation should therefore consider local and site-specific characteristics [27,48,50]. Jalili et al. [38] therefore call for a bottom-up approach, in which consideration for the variations in size, layout, and site-specific characteristics among OWFs can be addressed, which closely assesses duration, vessel/equipment parameters, and other relevant factors. The aforementioned risk for precedent effects of abandonment could also be mitigated through a careful case-by-case evaluation [26].

Multi-Criteria Decision Analysis (MCDA) may be applied to evaluate decommissioning alternatives, as proposed by [46,70] and [25]. MCDA includes a decision-making or supporting approach in which different marine management alternatives are evaluated based on (often interdisciplinary, cross-sectoral) criteria selection, scoring and weighting, providing flexibility and adaptability for case-by-case evaluation. MCDA seamlessly addresses the three challenges of decommissioning decision-making for offshore wind farms: it allows stakeholders expertise and objectives to be involved in multiple phases of the evaluation [20,28], it provides a clear overview of trade-offs on multiple dimensions for different alternatives, and it allows for qualitative and quantitative data input [57,84]. Moreover, by incorporating criteria on other ocean users (e.g. opportunity costs for fisheries and protection potential), an MCDA can be seen as a more comprehensive tool for evaluating marine spatial management in general, rather than just for evaluating decommissioning alternatives.

Furthermore, precisely for wicked challenges in marine management, Elliot [18] proposed the governance framework '10-tenets for integrated, successful and sustainable environmental management' and includes 10 aspects to be taken into account in tackling marine challenges in decision-making: ecologically sustainable, technologically feasible, economically viable, socially desirable/tolerable, legally permissible, administratively achievable, politically expedient, ethically defensible (morally correct), culturally inclusive and effectively communicable. By ensuring connectivity between natural and social dimensions in decision-making, the framework assists in navigating wicked problems [18]. Smyth et al. [75] argue, therefore, that this is also an appropriate framework to consider when approaching integral decision-making for OWF decommissioning alternatives. We propose that such an MCDA should be built upon the 10-tenet framework [18] or that the outcome of the decision-making process should be evaluatedto examine whether it could provide an integrated, successful and sustainable alternative.

However, a lack of empirical data and practical experience currently complicates a case-by-case analysis [38,50]. Considering alternative decommissioning methods is hitherto theoretical of nature due to statutory barriers arising from both national permits [78] and international policies (IMO, UNCLOS, OSPAR Decision 98/3). Therefore, we emphasize the need for pilot projects, which allows for technical experiences and environmental monitoring to substantiate trade-off analysis of various decommissioning alternatives. Fowler et al. [27], for instance, propose a 'temporary suspension of obligatory removal to facilitate research', which allows for in-situ monitoring to increase scientific knowledge of environmental effects [50]. Solely by obtaining empirical evidence can potential permanent regulatory changes be substantiated [47] and provide robust evidence-based decision-making and management [50].

7. Conclusion

While the first offshore wind farms are approaching their end-of-life and a plethora of scientific papers on decommissioning alternatives can be found, the public political debate on how to approach decommissioning is still in its infancy. This study firstly emphasised the multifaceted 'wicked' nature of decommissioning, which highlights the challenge of determining a singular, optimal solution. Evaluating alternative options therefore necessitates a nuanced understanding of the advantages and disadvantages for each stakeholder involved, acknowledging the complexity of balancing competing interests. Therefore, through stakeholder input, this study has provided the first guidance for the Dutch case study on what the broadly supported criteria are to enable this trade-off exercise. The next step would be to operationalise the criteria in future research; i.e. by adding indicators, units of measurement and data sources where possible.

While recent discussions on the potential ecological benefits of OWFs seem to indirectly and perhaps subconsciously put forward partial decommissioning as an almost legitimate alternative, this study has exposed stakeholders' concerns that the true 'value' of these ecosystems must first be defined to avoid artificial reefs of convenience and a precedent effect. Furthermore, this study has highlighted the need to look beyond this integral approach of evaluating decommissioning alternatives already. While rigid regulations appear to be the main obstacle to enabling alternatives to full decommissioning, uncertainties around residual liability (costs and responsibilities) are still likely to be a major barrier to actually implementing these methods, should they be allowed. Therefore, a greater push towards creating regulatory clarity and guidelines, in parallel with initiating a holistic evaluation of decommissioning options, is deemed crucial to enable industry parties to timely plan an environmentally, socially and economically balanced decommissioning phase.

Lastly, embracing a participatory and adaptive governance framework ensures that decisions are substantiated by involving the diverse perspectives and interests of stakeholders, ideally finding a solution in which trade-offs can be minimised. Recognising that each decommissioning scenario is unique, due to its localised and context-specific character, a case-by-case approach is thereby imperative. Avoid perpetuating a lock-in scenario by embracing a case-by-case approach and promoting a culture of learning-by-doing.

While this study has predominantly focused on the case of the Netherlands, offshore wind farm decommissioning is of global concern. Navigating the landscape of decommissioning decision-making and the pursuit of sustainable outcomes requires not only a thorough awareness of the trade-offs but also a commitment to collaborative, adaptive governance that engages stakeholders in shaping the future of sustainable marine management.

Author Agreement Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

CRediT authorship contribution statement

Luc van Hoof: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Lobke H. Jurrius:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization.

Declaration of Competing Interest

There are no conflicts of interest to declare.

Data Availability

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