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Providing room for nature in offshore wind decommissioning in the Netherlands

Participatory multi-criteria analysis of decommissioning strategies for offshore wind foundations, based on economic, environmental and social dimensions

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Abstract

At offshore wind turbine foundations, the marine habitat thrives due to artificial reef effects and fishery exclusion-zones. Nevertheless, in the Netherlands, these structures will have to be fully removed after roughly 30 years owing to their technological lifespan and inflexible regulations. The role of and impacts on nature are not adequately addressed in decommissioning decision-making, and simultaneously there is insufficient stakeholder involvement in the decision-making process. Thus, momentum has been gained to approach decommissioning in a more holistic and interdisciplinary manner. This study meets both demands by examining various foundation decommissioning strategies through a participatory multicriteria analysis, involving key stakeholders through information provision and individual interest advocacy. Building on the *triple bottom line* framework and *transition management* theories, decommissioning strategies were tested on interdisciplinary criteria, which enabled overview of trade-offs between strategies and stakeholders. Prinses-Amalia windfarm was assigned as case-study. Amongst others, the analysis shows that there is a considerable overlap among stakeholders in terms of preferred strategies, albeit due to different motivations. Especially when leaving scour behind combined while maintaining some exclusion-zone, an widely-accepted, profitable and sustainable strategy is found. It provides multiple ecological advantages and eliminates dreaded residual liability, though it brings challenges of fisheries lobbying, precedent effects and political incompatibility. Moreover, the conception of 'environmentally beneficial' differs significantly among stakeholders, having a major impact on the preferred strategy. Establishing an actor-network and pilot-site is recommended to ensure common ground in terms of concepts, goals and interests, so that informed decisions can be made leading to long-term sustainability.

Acknowledgements

Being at the end of my educational journey, I could not have thought of a better capstone than conducting this specific research for my Master's thesis. The overlap of resource management, the marine ecosystem and the energy transition, is something I feel very inspired by. I learned a lot in the field of stakeholder participation, transition management, conducting interviews and working with both qualitative as well as quantitative data in a relatively unexplored research domain.

Firstly, I am grateful to Hanna Dijkstra and Lotte van Oosterhout who gave me the confidence and freedom to take the opportunity to conduct this research outside of the University, and Pieter van Beukering for his affirmative support. Their expertise, continuous enthusiasm and constructive feedback have helped me tremendously throughout the project. In addition, this research would not have been possible without Suuz Kamper who welcomed me with open arms as a graduation intern at ECHT, where I was immediately warmly welcomed by an ambitious team. Also thanks to Maarten Lobregt, who was always there for support with his positive and inexhaustible energy, and last but not least, without the trust and support of Erwin Coolen and Hans Timmers, I would not have had the opportunity to gain this experience at a great workplace during my graduate studies. Of course, without all the stakeholder representatives who welcomed me so openly to ask questions, shared my enthusiasm and were always open to further contact if necessary, this project would not have been such a rewarding experience. I would like to thank them for that.

I am approaching the end of this study with a mind full of new insights and inspiration. Hopefully by reading this thesis, I will be able to share this knowledge and excitement with you as a reader as well.

Contents

List of acronyms

BS	Below seabed alternative
CR	Complete removal alternative
DRA	Designated reefing area
eNGO	Environmental non-governmental organization
IMO	International Maritime Organization
MCA	Multi-criteria Analysis
MPA	Marine protected area
NGO	Non-governmental organization
O&G	Oil and gas
OSPAR	Oslo and Paris Commissions Convention
OWEZ	Offshore Windfarm Egmond aan Zee
OWF	Offshore wind farm
PAWP	Prinses Amalia Wind Park
SP	Scour protection alternative
SPMPA	Scour protection combined with marine protected area alternative
T	Topping alternative
TBL	Triple Bottom Line
TMPA	Topping combined with marine protected area alternative

1. Introduction

In the recent Climate Agreement, the Dutch government set the goal of a carbon-neutral energy supply by 2050 (Rijksoverheid, 2019). To achieve this ambitious target, offshore wind energy has become a main pillar of climate policy (Rijksoverheid, n.d.-b). The North Sea is highly suitable for offshore wind energy due to its relatively shallow depth, close proximity to ports and favorable windy climate ((Rijksoverheid, n.d.-b). Additionally, decreasing costs made offshore wind energy the most affordable large-scale renewable energy source (Rijksoverheid, n.d.-b. Currently 133 km^2 (approximately 0,23%) of the Dutch North Sea is used for offshore wind farms (OWFs), which will increase to 1600 km^2 (2,8%) by 2030 (Rijksoverheid, n.d.). These OWFs will provide 8.5% of all energy use, as well as 40% of current electricity consumption in the Netherlands (Rijksoverheid, n.d.-b).

Simultaneously, the Dutch North Sea is subject to environmental objectives regarding nature recovery and conservation (Fowler et al., 2020). The seabed was once largely covered with biogenic substrates (e.g. oyster reefs), though these have almost completely disappeared due to anthropogenic activities, such as bottom-trawling fisheries (van Duren et al., 2016; Fowler et al., 2020). The recent North Sea Agreement acknowledges that "biodiversity is declining and soils are disturbed" and as pressure from bottom-disturbing activities continues, the likelihood of natural recovery of these biogenic reefs is minimal (van Duren et al., 2016). Yet, as argued in the North Sea Agreement, "objects and installations that create new habitats can contribute to nature restoration" as they provide hard substrate in a dominantly soft sediment environment (Rijksoverheid, 2020, p. 11; Birchenough & Degraer, 2020). Marine species use such new habitat to settle, spawn, forage and refuge, thereby increasing local biodiversity and biomass, so-called 'artificial reef effects' (Birchenough & Degraer, 2020; Coolen et al., 2020; Fowler et al., 2018; Teunis et al., 2021).

Offshore wind structures also have been found to induce artificial reef effects, of which Figure 1 shows an overview (Degraer et al., 2020). The heterogeneity of habitat created by the steel structure and the surrounding erosion protection, which consists out of loose rocks, provides opportunities for a variety of species from multiple levels in the food web (Degraer et al., 2020; Lengkeek et al., 2017; van Duren et al., 2016). Additionally, OWFs are prohibited from trawl-fisheries and heavy vessels, consequently protecting the area from bottom-disturbing activities[1]. Thereby the opportunity for environmental flourishment is strengthened (van Duren et al., 2016; Ounanian et al., 2020).

Consequently, OWFs could represent an effective overlap between nature and energy targets at sea. It is however unlikely that these thriving habitats will exist indefinitely, because at some point OWFs will have to be decommissioned, i.e. dismantled and removed (Fowler et al., 2018). The first Dutch OWFs to be decommissioned will be the Egmond Aan Zee and Prinses Amalia wind farms, in 2026 and 2027 respectively (Teunis et al., 2021). An offshore wind turbine lasts for approximately 20-30 years before being no longer profitable due to failure or fatigue (Smyth et al., 2014). Moreover, permits granted for offshore wind sites are

[1] Policy for establishing safety zone for offshore wind farms, at https://wetten.overheid.nl/BWBR0042533/2018-05-01

only valid for 30 years in the Netherlands, and include an obligation to remove all structures when this period ends (Teunis et al., 2021).

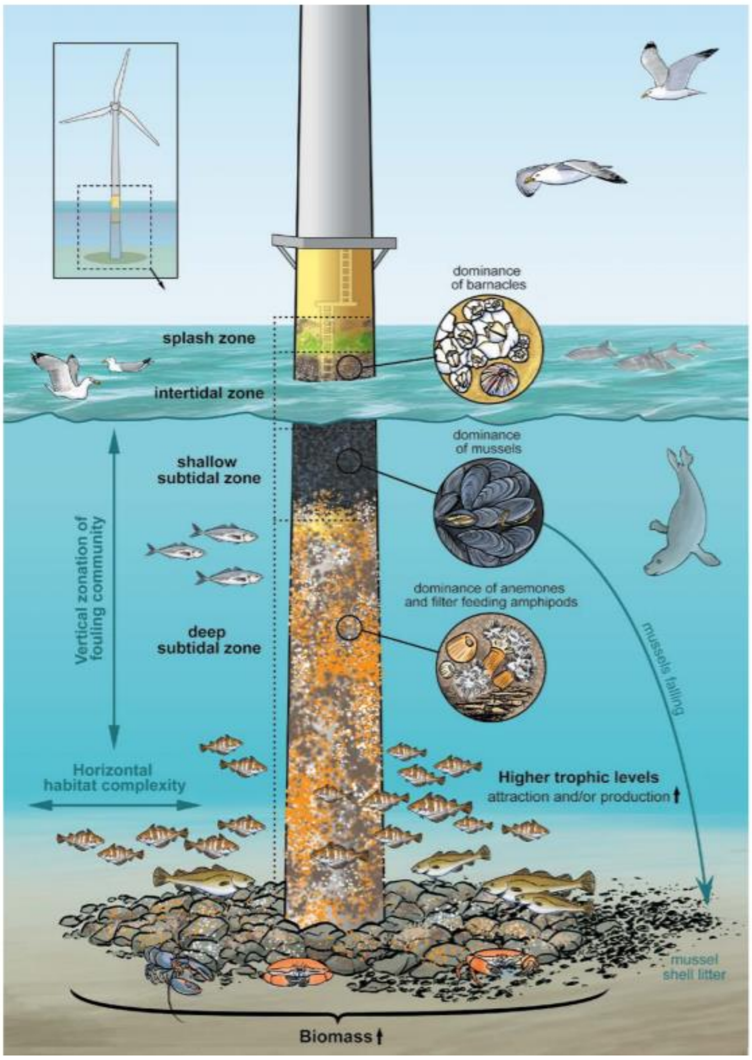

Figure 1. Artificial reef effects at offshore wind monopile installation and surrounding scour protection (Degraer et al., 2020)

International and national regulations currently require the seabed to be fully cleared from structures (Teunis et al., 2021). Internationally, the International Maritime Organization (IMO) and the United Nations Convention on the Law of the Sea Article 60(3) explicitly obligate the entire removal of installations (Smyth et al., 2015). Regionally, the Oslo and Paris Commissions Convention (OSPAR) Decision 98/3 furthermore states that artificial reefs may only be deliberately constructed through targeted new projects, leaving little room for the abandonment of energy structures for the purpose of constructing reefs (Ounanian et al., 2020). Removal of OWFs thus seems inevitable.

Consequently, in light of the ecological benefits these offshore structures provide, scientific consensus is reached to review current decommissioning laws and regulations (Fowler et al., 2020). Complete removal will not only eliminate artificial reef effects, but also reopen the area to bottom-disturbing trawl fisheries (Adedipe & Shafiee, 2021; Fowler et al., 2018; Fowler et al., 2020; Kerkvliet & Polatidis, 2016; Smyth et al., 2014). Contrastingly, leaving parts of the foundations in place could minimize decommissioning impacts, safeguard established nature from further seabed disturbance, and potentially support conservation targets (Ounanian et al., 2020; Topham et al., 2019). Therefore, according to Smyth et al. (2014), such partial removal should shift away from being considered as 'dumping' to be viewed as 'support' for nature.

1.1. Problem definition

Despite the aforementioned artificial reef effects, consideration of ecosystem functioning has not yet permeated the decision-making process on decommissioning strategies, nor have ecological criteria been adequately addressed in regulation (Fowler et al., 2020). Also within Environmental Impact Assessments, the decommissioning phase is often underrepresented as it is regarded too far in the future (Smyth et al., 2015). Nevertheless, Adepipe and Shafiee (2021) argue that to ensure cost-effective decommissioning practices, wind farm operators (i.e. permit-holders) should plan the decommissioning early in the operational phase. Yet due to limited experience (Adedipe & Shafiee, 2021; Topham et al., 2019) and ill-defined decommissioning regulations (Fowler et al., 2020) actually planning the decommissioning of offshore wind turbines is proving to be challenging (Topham et al., 2019).

In addition to these ecological and financial implications, decommissioning decisions are socially and politically sensitive due to the involvement of many stakeholders that have a wide variety in interests (Kerkvliet & Polatidis, 2016; Martins et al., 2020). Therefore, to avoid unbalanced decision-making, stakeholder involvement should be an indispensable part of decommissioning decision-making processes (Fowler et al., 2015; Fowler et al., 2020; Kerkvliet & Polatidis, 2016; Smyth et al., 2014). Birchenough and Degraer (2020) argue that besides scientists, the wind industry and policy makers, also the wider public needs to be engaged to ensure a widely accepted outcome. Especially environmental non-governmental organizations (eNGOs) should be included due to the inevitable environmental aspects involved (Martins et al., 2020). However, sufficient stakeholder engagement has been lacking in offshore wind decommissioning criteria analyses, or have included only hypothetical stakeholder involvement (Fowler et al., 2015; Fowler et al., 2020; Kerkvliet & Polatidis, 2016). By involving stakeholders early in the decision-making process, thereby taking their expertise, opinions and visions into account, a level of stakeholder engagement that is often missing in current frameworks could be provided.

Concluding, there exists a clear demand for holistic and inclusive approach to understand how decommissioning can be made economically, environmentally and socially sustainable (Fowler et al., 2015; Smyth et al., 2014; Techera & Chandler, 2015; Tickell et al., 2019). This variety of factors has thus far not been sufficiently highlighted in decision-making yet (Fowler et al., 2018; Gjødvad & Ibsen, 2016; Smyth et al., 2014). The demand for nature-preserving decommissioning provides a window of opportunity to establish more carefully planned and inclusive policies (Ounanian et al., 2020). Accordingly, this study responds to both the demand for participatory as well as interdisciplinary decommissioning analysis by answering the following question and sub-questions:

What opportunities currently exist for implementing nature-preserving decommissioning strategies of offshore wind turbine foundations in the Netherlands?

- *What stakeholders define the offshore wind decommissioning playing field?*
- *Taking into account stakeholder interests, how do different decommissioning strategies score on economic, social and environmental criteria?*
- *What trade-offs are found when pursuing nature-preserving decommissioning strategies?*
- *What recommendations can be made based on the results?*

1.2. Research outline

The theoretical framework and methodological framework in which the study is situated will first be refined (Chapter 2 and 3). Thereafter, the stakeholders and their position in the offshore wind decommissioning playing field are examined (Chapter 4). Subsequently, seven foundation decommissioning strategies are analyzed based on ten economic, social and environmental criteria (Chapter 5). This includes a selection process for the appropriate criteria and integration of stakeholder interests and concerns. After examining the results (Chapter 6) and thoroughly discussing them (Chapter 7), policy recommendations provided (Chapter 8).

2. Scientific framework

2.1. Theoretical framework

Underlying this research are two theories that include societal, environmental and economic dimensions to address societal challenges: Triple Bottom Line and the 10-tenets of integrated, successful and sustainable marine management. Additionally, the theory of transition management is examined, which aims at facilitating transition processes towards sustainable processes.

2.1.1. Triple Bottom Line

Initially proposed as an accounting framework, the Triple Bottom Line (TBL) intends to move beyond monetary values, i.e. profits and investments, by including social, economic and environmental dimensions (Figure 2) (Slaper & Hall, 2011). Integral sustainability is found where all three dimensions intersect. This framework aims to support sustainability goals or sustainable growth within businesses, but has also been widely addressed by governmental institutions and non-governmental organizations (NGOs) (Slaper & Hall, 2011). The importance per dimension and their sub-categories might differ per organization and among sustainability targets, therefore stakeholder participation is considered crucial, according to Slaper & Hall (2011).

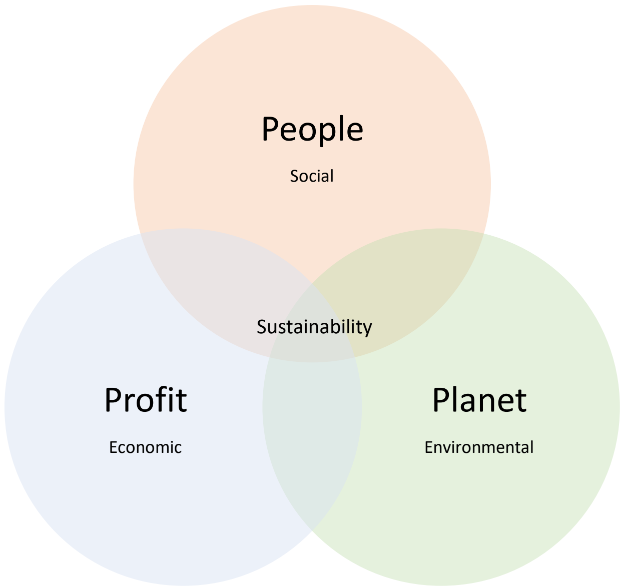

Figure 2. Triple Bottom Line framework

2.1.2. The 10-tenets of integrated, successful and sustainable marine management

The 10-tenets framework, proposed by Elliott (2013), builds upon the TBL framework to support marine management, yet includes seven additional pillars: legal, administrative, technological, cultural, ethical, communication, and political. Especially this latter dimension is considered indispensable, since even if all other dimensions are met, sustainable environmental management is not possible without the agreement and support of the political authorities (Elliott, 2013).

The framework is highly useful for decision-making processes in interdisciplinary contexts, such as complex environmental management challenges that include multiple stakeholders and multiple disciplines (Smyth et al., 2014). Accordingly, Smyth et al. (2014) argue that also for offshore wind decommissioning decision-making it is a suitable framework to be considered. Table 1 provides an overview of the 10-tenets, their definition and an example for its application to OWFs, as provided by Smyth et al. (2014).

Table 1. The 10-tenets for integrated, successful and sustainable environmental management (Elliott, 2013) accompanied by a selection of examples provided in Smyth et al. (2014) for its application to offshore wind decommissioning

Tenet (Elliot, 2013)	**Definition**	**Example OWF (Smyth et al. 2014)**
Ecologically sustainable	Measures will ensure that the ecosystem functioning and provision of ecosystem services are safeguard	Natural ecology is not disrupted during decommissioning
Technologically feasible	Methods, techniques and equipment for ecosystem and society/infrastructure protection are available	Methods of removing all or part of the structure are approved
Economically viable	A cost-benefit assessment of the environmental management indicates (economic) viability and sustainability	During decommissioning the costs of full or partial removal are economically justified
Socially desirable/tolerable	Environmental management measures are as required or at least are understood and tolerated by society as being required	If partial decommissioning occurs then society sanctions the structures left in place
Ethically defensible (morally correct)	The wishes and practices of individuals are respected in decision-making	Dealings with individuals are at the highest level and that no single sector is favored unduly
Culturally inclusive	Local customs and practices are protected and respected	Effects of full or partial decommissioning on indigenous fisheries are taken into account
Legally permissible	There are regional, national or international agreements and/or statutes which will enable and/or force the management measures to be performed	Shipping and navigational safety are ensured; that there is legal sanctioning of partial decommissioning
Administratively achievable	The statutory bodies such as governmental departments, environmental protection and conservation bodies are in place and functioning to enable successful and sustainable management	Communication between statutory, planning, legal and environmental bodies ensures coherent implementation
Effectively communicable	All horizontal links and vertical hierarchies of governance are accommodated and decision-making is inclusive	All stakeholders have the opportunity to participate in decision-making
Politically expedient	The management approaches and philosophies are consistent with the prevailing political climate and have the support of political leaders	There is pressure on politicians to carry out measures

2.1.3. Transition management

Due to the complexity of societal systems, it is hard to predict when and where to steer processes towards sustainability (Loorbach, 2007). Moreover, systems often become locked in a steady state or become path-dependent, hence are difficult to move out of a particular equilibrium (Loorbach, 2007). Occasionally a window of opportunity exists to realize a change towards more sustainable societal practices (Loorbach, 2007).

Transition management is a governance approach seeking to accelerate and understand transition processes to link “long-term sustainability to desired societal transitions” (Loorbach, 2010, p. 163). ‘Transitions’ are co-evolving economic, societal, ecological and technological developments that eventually lead to system changes (Kemp et al., 2003; Rotmans & Loorbach, 2009).

Although ‘transition policy’ is vaguely defined in the literature, as it relies more on a policy *approach* than on specific policy *instruments*, it appears to be characterized by three main pillars. Firstly, they are often described as long-term and adaptive, rather than focused on short-term success (Elzen, et al., 2004; Kern & Smith, 2008). Secondly, they strive to create actor-networks to get grip on transition processes (Loorbach, 2007), thereby not forcing changes but facilitating it (Elzen, et al., 2004). By actively engaging various perspectives of stakeholders, public legitimacy can also be secured (Hendriks, 2009). Thirdly, Elzen et al. (2004) state that a philosophy of ‘learning-by-doing’ characterizes transition management, in which learning about a wide variety of perspectives and solutions is key. Concluding, a multi-domain and multi-actor approach is crucial to establish sustainable and adaptive policies (Elzen et al., 2004; Kemp et al., 2003; Kern & Smith, 2008; Loorbach, 2007).

2.2. Conceptual framework

Based on these theoretical frameworks, the conceptual framework in Figure 3 has been created for this particular study. It incorporates TBL, the 10-tenets and transition management into an inclusive, adaptive and holistic decision-making tool.

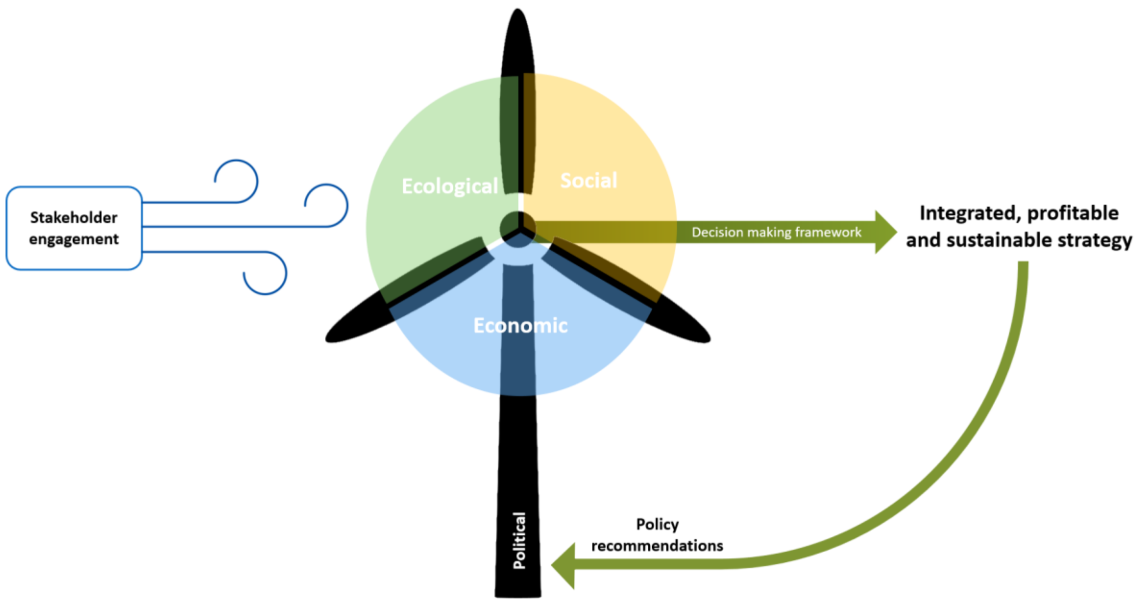

Figure 3. Conceptual framework of inclusive, adaptive and supportive decision-making within offshore wind decommissioning

The turbine represents the interdisciplinary domains in which decommissioning decision-making is located: the blades represent the social, ecological and economic domains that should be taken into account, while the base-structure is the political domain. The reason for the latter being the base of the turbine is, as the 10-tenets framework shows, integrated and sustainable management is impossible without support from politicians (Elliott, 2013).

To be informed of current developments while strengthening the support for decisions, stakeholder involvement is necessary to *energize* the decision-making process. This includes providing information on what strategies are feasible and what criteria should be considered, as well as indicating their individual interests to allow examination of trade-offs between stakeholders. Resultingly, a decision-making framework can be formed that provides an overview of various alternatives with associated opportunities and threats. Ultimately this provides rationale for an integrated, profitable and sustainable strategy.

The findings can be provided as inclusive and well-founded feedback towards the foundation of the structure, the political domain. Such policy recommendations should be focused on the three pillars of transition management (long-term, network based and learning-by-doing), in order to ensure integrated sustainability. The political climate can act upon these recommendations, possibly by modifying regulations. Since the interests of stakeholders are constantly changing in response to societal developments and policy changes, the process can be repeated. This feedback loop ensures that new decommissioning strategies are constantly researched, applied and reviewed, to arrive at the most optimal strategy available at any given moment.

3. Methodology

3.1. Research methods

To achieve the research objectives, a participatory multi-criteria analysis (MCA) is recommended to provide a holistic and inclusive evaluation of decommissioning strategies (Kerkvliet & Polatidis, 2016; Rozemeijer et al., 2016). MCA is a well-established decision support method, that allows for comparison between alternatives by investigating their scores on various criteria, using both qualitative and quantitative data sources (Brander & van Beukering, 2015; Martins et al., 2020). 'Participatory' refers to the inclusion of multiple stakeholders in both the development and operation of the model (Fowler et al., 2015). An MCA is conducted in several steps (Figure 4).

First, the various decommissioning alternatives to be examined are defined. To assess the impact of these alternatives, appropriate criteria are selected against which they are evaluated. Combination of the selected alternatives (horizontally) and criteria (vertically) make up the effects table, to which scores are then assigned with a variety of metrics. Standardizing these scores is required to allow for (mathematical) comparison between criteria (Brander & van Beukering, 2015). Thereafter, in the valuation and evaluation phase, criteria are given weight to indicate their relative importance. Subsequently, ranking of the alternatives is calculated by multiplying the weights by the assigned scores. A sensitivity analysis should be conducted to examine the robustness of the MCA, examine areas of uncertainty and analyze the impact that plausible scenarios could have (Brander & van Beukering, 2015; Fowler et al., 2014; Henrion et al., 2015; Martins et al., 2020). Finally, based on these results, recommendations can be made. Stakeholders are involved in the selection of criteria, provision of relevant data for scoring, and assignment of weights.

The suitability of MCA for this study is twofold. Firstly, the required data sets do not have to be in similar metrics, which enables the inclusion of both qualitative and quantitative data (Brander & van Beukering, 2015). Hence it suitable for studying new areas of research, such as OWF decommissioning, where the type of data to be collected may vary according to the criteria, including non-monetary or hard-to-quantify data. Moreover, MCA provides stakeholders the ability to clearly oversee different deliberately chosen criteria and alternatives, and negotiate accordingly due to the openness and traceability of the process (Brander & van Beukering, 2015; Kerkvliet & Polatidis, 2016).

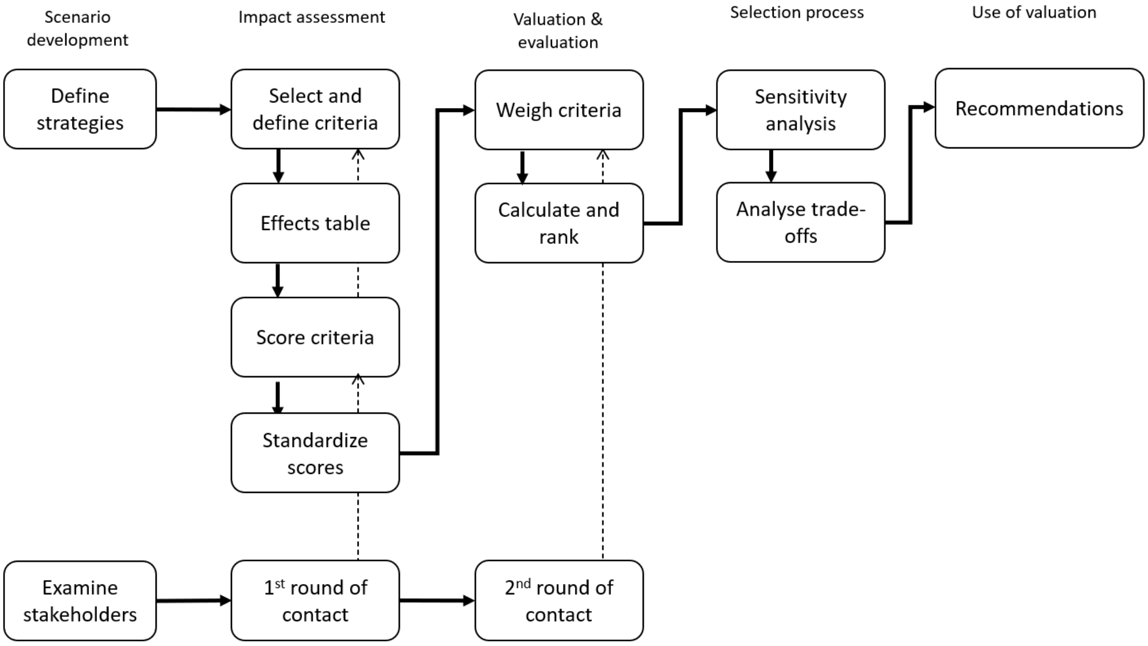

Figure 4. Methodological steps in participatory multi-criteria analysis (including steps of MCA derived from Brander & van Beukering, 2015, Figure 7.4)

3.2. Data collection

Data was gathered through literature review and semi-structured interviews. Literature research was carried out to analyze the decommissioning playing field; to determine decommissioning strategies; to review previously used and recommended decommissioning decision-making criteria; and to score the effects table. To find suitable literature, Google Scholar and Google Search have been used. Reports and peer reviewed articles on wind, oil and gas decommissioning were consulted.

Stakeholders were consulted at two moments. First by means of a semi-structured interview, to gather feedback on selected criteria and to gather data for scoring. 'Semi-structured' means using a question-list with predetermined subjects, but allowing flexibility to dive further into the subjects and responses if desired. Interviewees were contacted through email or phone. Stakeholders were selected for their expected affiliation with offshore decommissioning. Eventually 19 interviews have been conducted, which were recorded and transcribed (Table 2). For reasons of anonymity, all data collected from stakeholders is referred to by grouped names (e.g. *Contractor 1*). Later, stakeholders were contacted by email to assign weights to the final criteria selection. For weighting, a point-awarding method is used. Stakeholders were asked to divide a total of 100 points over the categories to indicate their importance, which are subsequently redivided over the sub-criteria.

Especially a thorough process was used to select integrated and supported criteria for the MCA. First, previously applied criteria were analyzed and contextualized in the triple-bottom-line framework to ensure a holistic overview. Based on this, a preliminary criteria selection was made by industry experts (ECHT, personal communication, 2021). This selection was then supplemented and adjusted with stakeholder feedback from interviews.

Table 2: Overview of conducted interviews

Interview	Date	Stakeholder group	Referred to in text as..	Weights provided?
1	03/05/2021	Marine environmental consultant	*Consultant 1*	Yes
2	06/05/2021	Marine environmental consultant	*Consultant 2*	Yes
3	20/05/2021	Marine ecologist	*Marine ecologist 1*	Yes
4	21/05/2021	Environmental NGO	*eNGO 1*	Yes
5	06/05/2021	Environmental NGO	*eNGO 2*	Yes
6	07/05/2021	Environmental NGO	*eNGO 3*	Yes
7	06/05/2021	Operator/permit-holder	*Operator 1*	No
8	28/04/2021	Operator/permit-holder	*Operator 2*	Yes
9	through mail	Contractor	*Contractor 1*	Yes
10	12/05/2021	Contractor	*Contractor 2*	Yes
11	25/05/2021	Contractor	*Contractor 3*	Yes
12	28/04/2021	Contractor	*Contractor 4*	Yes
13	20/05/2021	Governmental organization	*Govt 1*	No
14	26/05/2021	Governmental organization	*Govt 2*	No
15	14/05/2021	Governmental organization	*Govt 3*	Yes
16	28/04/2021	Sector association	*Sector association 1*	Yes[2]
17	27/05/2021	Recreational sector	*Recreation 1*	No
18	04/05/2021	Fishing industry	*Fisheries 1*	No
19	10/05/2021	Oil and gas sector	*O&G 1*	No

3.2.1. Case study

Since OWFs differ in site size, number of present turbines, monopiles dimensions and in terms of location, specific MCA outcomes might differ per OWF. Therefore, Prinses Amalia Wind Park (PAWP) was chosen as a case study for this analysis, as it is one of the first OWFs to be decommissioned. PAWP is located off the coast of Ijmuiden, 23 to 36 kilometers offshore, and covers an area of 14km^2 (Figure 5).

[2] Weights excluded in MCA owing to their specific position in the stakeholder field, not falling into one of the 6 key stakeholder groups

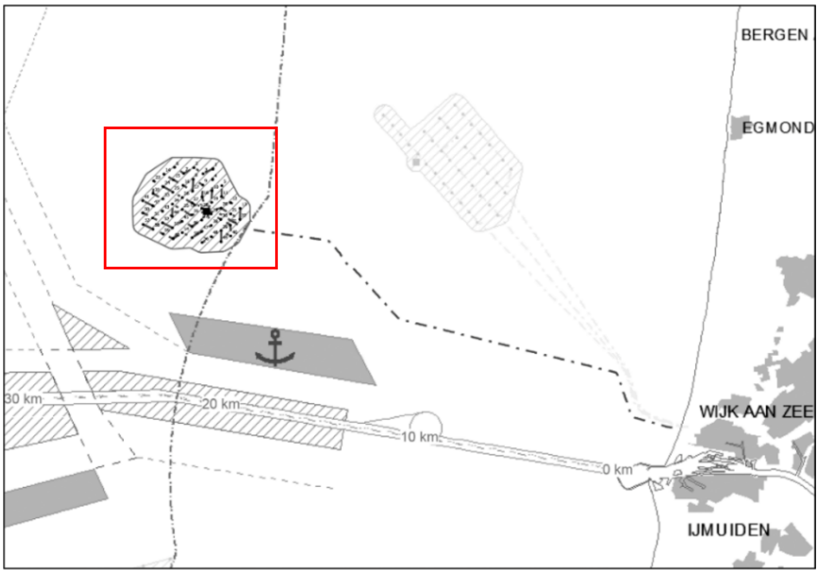

Figure 5. Location of offshore wind farm Prinses Amalia (PAWP). Offshore wind farm OWEZ in light grey on its right. Also indicated are cable infrastructures, shipping routes and anchorage site[3]

3.3. Data analysis

The analysis does not provide a conclusion on the 'perfect' alternative, as results are highly dependent on assumptions made in scoring and weighting, and the sample of stakeholders consulted. However, it does provide a transparent exploratory analysis and provides a foundation for further analysis (Kerkvliet & Polatidis, 2016). MCA results were analyzed on differences and trade-offs between alternatives, criteria, and stakeholders. Besides a sensitivity-analysis, several scenario-analyses were conducted to examine the effects of plausible developments in the playing field. The seemingly most beneficial alternative was evaluated against the 10-tenets framework to examine whether it could provide an integrated, successful and sustainable alternative. Ultimately, policy recommendations were formulated based on these results, keeping the pillars of transition management in mind.

[3] Map of Prinses Amalia wind farm found at https://zoek.officielebekendmakingen.nl/stcrt-2018-22895.html

4. Offshore wind decommissioning stakeholders

As aforementioned, decommissioning decisions are politically sensitive due to the involvement of many stakeholders that are accompanied by a variety in interests. Based on expert consultations and interview input, an overview of the offshore wind decommissioning playing field in the Netherlands is shown in Figure 6. This section briefly examines the stakeholders involved, and their involvement in and familiarity with the decommissioning of OWFs.

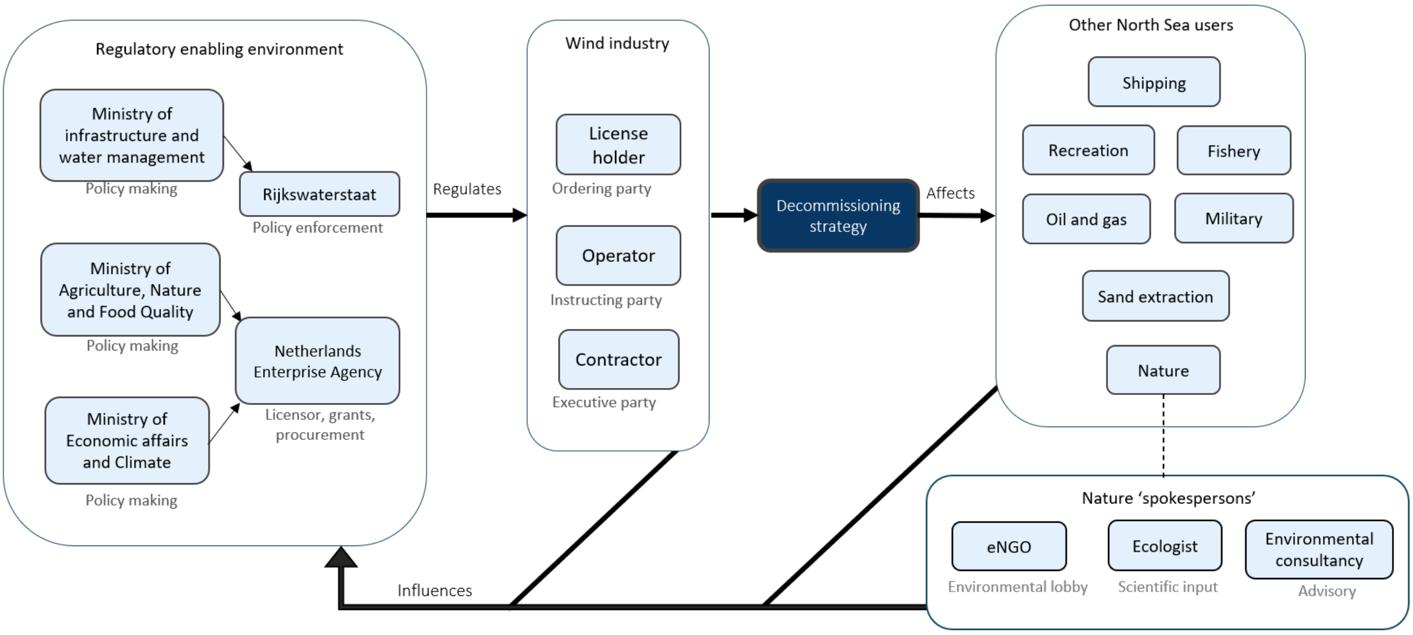

Figure 6. Overview of stakeholders within offshore wind foundation decommissioning playing field in the Netherlands

Regulatory enabling environment

The regulatory environment consists of governing parties, who together form and enforce policies, regulations, and national objectives (*Govt 1*). Each Ministry has a different focus on societal challenges, bringing other disciplines more prominently forward, e.g. establishing nature targets or regulating the energy transition (*Govt 1*). While Ministries develop policy, other governmental agencies provide policy enforcement or licensing. Policies include the issuance of a permit for a particular site at sea, the requirements for both the construction and deconstruction of a wind farm, but also regulations regarding how nature should be included.

The decisions made within this regulatory framework, influence the arena in which the wind industry makes its choices regarding which decommissioning strategy to pursue. Yet, from interviews it appears these decisions are not always clearly communicated. Table 3 shows several interview-statements on such regulatory matters, which shows both uncertainties and contradictions among stakeholders. For example, despite not specifically incorporated by law, 6 meter below seabed removal of structures is commonly expected in the

Netherlands (Teunis et al, 2021), yet also depths of 2, 4 and 5 meters depth are mentioned (*Operator 2, Contractor 1;* Kerkvliet & Polatidis, 2016; Smyth et al., 2014).

Table 3. Statements from interviews on views on jurisdictional playing field of offshore decommissioning

Interview	Statement
Operator 2	*"There is just a **lot of ambiguity [in the legal area].** Now it's just super tight, this is not allowed, this is allowed. But something does seem to be moving in that whole sector."*
Fisheries 1	*"The only thing that is said to us is: **it will all be cleaned up**."*
Operator 2	*"In the Netherlands, they said you had to **cut the monopiles off 5 meter below the seabed**. These are rules that differ from country to country."*
Contractor 1	*"For the time being, the monopiles are expected to be **cut to 2 meter below the seabed**"*

Wind industry

The wind industry stakeholders consist out of permit-holders, operators and contractors (ECHT, personal communication, 2021). OWF permit-holders -those who have been granted temporary access to a particular site- and OWF operators -those who actually develop and operate the installed wind farms- are often the same party in the Netherlands. Moreover, offshore contractors are indispensable stakeholders, given their direct involvement in the process through actual execution of OWF installation and decommissioning (ECHT, personal communication, 2021). From interviews, it is evident that concrete action has not yet been taken, yet decommissioning is increasingly being discussed by wind industry stakeholders (Table 4Table *3*). Although reluctance may play a role, discussing decommissioning is sometimes considered premature or argue that more research needs to be conducted first.

Table 4. Statements from interviews on involvement and topicality of offshore decommissioning

Interview	Statement
Operator 1	*"I think **now would be a good time to probably assess the costs and benefits** of various options to make an informed choice on what to do. Because you could argue that by leaving some of the foundations in place, we would **save a lot of costs** and you could get more positive environmental impacts by spending the money in other ways."*
Operator 2	*"**We are currently investigating this issue** to see whether the estimated costs to decommission the installation, are realistic. […] And also who is capable of decommissioning it at all?*
Contractor 2	*"Yes, **so it is being considered but it is not our top priority yet**. […] It's starting to slowly move towards a little bit more priority and slowly customers are also starting to ask questions about it."*
Contractor 3	*"I must say that offshore wind decommissioning is **still at a very early stage**."*

Other stakeholders

Decommissioning may affect other North Sea users, for example through navigational hindrance, safety risks or loss of fishing grounds if structures are left in place (Fowler et al., 2020). Coming into direct contact with these structures may lead to serious damage or even capsizing (Fowler et al., 2020). On the other hand, if no structures are left in situ, fisheries will likely regain access to these fishing grounds. Besides shipping (including military vessels) and fisheries, the affected groups also include oil and gas, sand extraction and nature (ECHT, personal communication, 2021; *Govt 2*). When structures are abandoned, oil, gas and sand extraction operations may be affected to some degree, as it will be more difficult to find usable extraction areas. Lastly, because nature cannot speak for itself, eNGOs, ecologists and consultants are grouped under 'nature's spokesperson'. All of these users of the North Sea engage in lobbying behavior towards the regulatory environment, which may influence choices being made here (ECHT, personal communication, 2021). In conclusion, the decommissioning playing field indeed involves a widely varying stakeholder group, where the political climate has underlying influence yet is also driven by industry and society.

5. Multi-criteria analysis

This section discusses the first steps of the multi-criteria analysis, beginning by identifying the decommissioning strategies and criteria. These together create the effects table, of which the scoring is then briefly summarized. Thereafter, individual weights provided by stakeholders are provided.

5.1. Foundation decommissioning alternatives

Various foundation types exist, but in the Netherlands mainly monopiles are used because of their suitability for relatively shallow depths of 10-30 meters (Gjødvad & Ibsen, 2016), small marine footprint compared to other bottom-fixed foundation structures (Kapsali & Kaldellis, 2012) and show low manufacturing, transport and installation costs[4]. Monopiles are steel piles that are driven into the seabed to a depth of over 22 meters (Kapsali & Kaldellis, 2012). Moreover, as sea currents erode the sediment surrounding the monopiles, a protection layer consisting out of loose rocks, called scour protection, is placed around the base counter this process (Teunis et al., 2021). Scour usually covers 4-6 times the monopile diameter (Lengkeek et al, 2017).

To be able to remove the monopile, first the turbine and transition piece have to be disassembled (Figure 7, Topham et al., 2019). Reusing the foundation structures by replacing the old turbine by an improved turbine, i.e. repowering, is an often mentioned strategy (Topham & McMillan, 2017). However, its potential for OWFs that will reach their end-of-life phase in the Netherlands in the near future is minimal. Their foundations do not offer sufficient support as modern turbines have grown rapidly in size (TNO, 2020[5]). This was confirmed in interviews, in which the size and lifespan of the foundations and the shallow sea depth, in addition to high spatial pressure, are mentioned as practical problems of repowering the earliest OWFs (*Govt 2, Contractor 2*). Hence, repowering of foundations was not further examined.

Although some studies have aimed for a holistic comparison between offshore foundation decommissioning strategies, these often compare them on 'high level' differences: full decommissioning versus partial decommissioning (Adedipe & Shafiee, 2021; Gjødvad & Ibsen, 2016; Smyth et al., 2014; Topham & McMillan, 2017). This study considers sub-options as well, together with the possibility of establishing a marine protected area (MPA). These strategies, as shown in Figure 7, are elaborated on further.

[4] Monopiles, at https://sif-group.com/en/products-services/monopiles-and-transition-pieces
[5] TNO is the Netherlands Organization for Applied Scientific Research

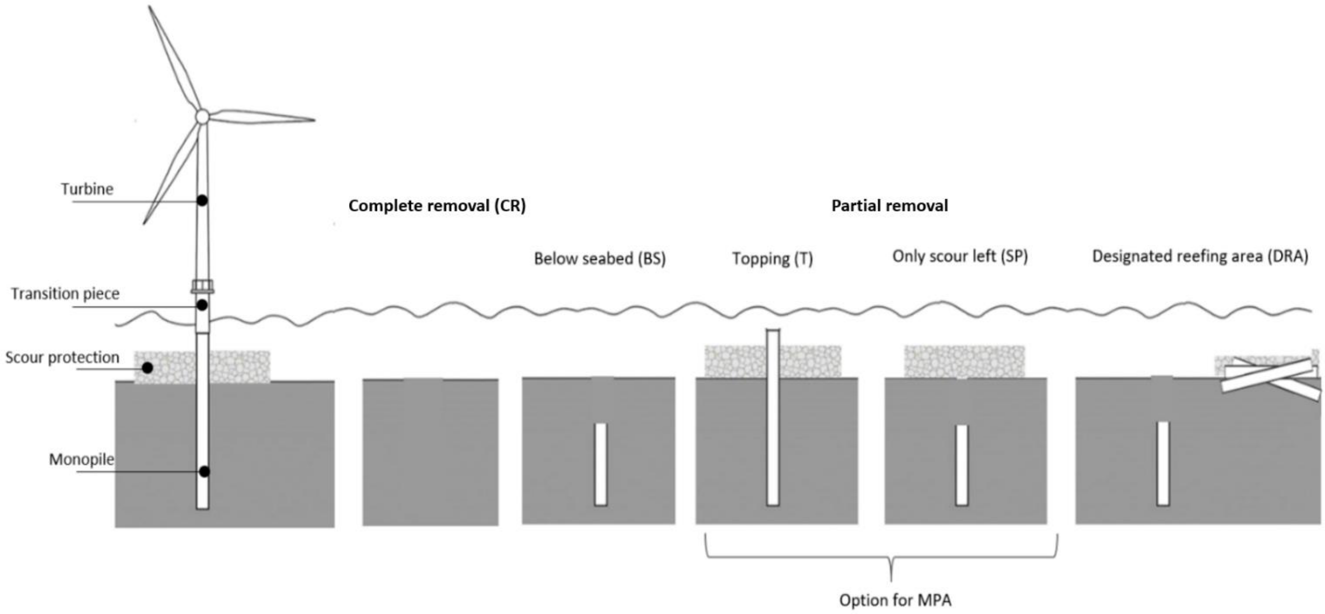

Figure 7. Overview of offshore wind turbine installation and the decommissioning strategies examined

5.1.1. Complete removal

In this alternative, the seabed is 'left as it was found', as the monopile is completely removed along with the surrounding scour. In discussions with *Contractors 2, 3* and *4*, uncertainty was expressed about how to completely remove a monopile in the North Sea. An often-mentioned concept is 'reversed installation technique' in which every part from top to bottom is removed piece by piece, mirrored to the installation order (*Contractor 1* and *2*). Scour may be removed first by using a grab-vessel (*Operator 1*). Dredging activities (i.e. removing surrounding soil) can be used to enable attachment of lifting-equipment to the pile (Topham & McMillan, 2017). Although Kerkvliet and Polatidis (2016) state that foundation structures are commonly removed in full by using explosives, a report by TNO (2020) elaborates on other technologies that are currently under development: hydraulic (pressurizing the monopile to force it loose) and vibratory (using vibrations to overcome fraction between soil and monopile) removal. Yet there still exists uncertainty about applying these methods on the open seas (*Contractor 4*).

5.1.2. Partial removal

In literature, 'Partial removal' often refers to cutting the pile a few meters below the seabed, leaving the remaining sub-seabed part in situ (Kerkvliet & Polatidis, 2016; Smyth et al., 2015). In this study, also alternative partial removal strategies were examined: topping, leaving only scour in place and using a designated reefing area. These alternatives have previously been described for the oil and gas (O&G) industry (Sommer et al., 2019). In all partial removal alternatives the monopile is cut, for which internal cutting is expected to be most cost-effective (Gjødvad & Ibsen, 2016; Kaiser & Snyder, 2010; Kerkvliet & Polatidis, 2016). *Contractors 2, 3* and *4* confirmed that most likely the monopile will be cut from the inside out.

A. Cutting below seabed

In this alternative, the monopile is cut approximately 4 to 5 meters below the seabed. As with full removal, it is expected that scour protection is removed by dredge-and-grab activities. Part of the monopile is left behind, yet will no longer noticeable after the seabed is resettled (Teunis et al., 2021).

B. Topping

'Topping' includes cutting the monopile a few meters above the seabed, thereby leaving scour in situ (Fowler et al., 2020). In this assessment it is assumed that the monopile is cut 2 meters above the seabed, yet other heights are also plausible (Fowler et al., 2020).

C. Only scour left in place

This alternative involves below seabed cutting, but leaving scour in situ. This is deemed a plausible scenario by *Govt 2*, *Contractor 4* and *Consultant 2*, and has been already mentioned in Danish decommissioning plans[6]. Their reasoning to execute this alternative includes reducing both environmental consequences and technical complexities.

D. Designated reefing area

'Reefing' involves repositioning structures elsewhere, in order to be purposefully deployed as an artificial reef (Sommer et al., 2019). Fortune & Paterson (2020) argue that this provides the possibility to deliberately create a thriving reef in a suitable and preferred area. In this assessment, it is assumed that the monopile is cut below seabed and the retained steel and scour are deposited in a designated reefing area. Due to lack of previous experiences, this study assumes that the DRA covers an area of 1 km^2.

5.1.3. Marine protected area

As an addition to the above-mentioned alternatives of Topping and leaving only scour in situ, the option to designate the site as marine protected area (MPA) after decommissioning is investigated. An MPA is defined by the European Environmental Agency (EEA) as "*geographically distinct zones for which protection objectives are set*"[7] and are an important attribute in both Dutch and European nature conservation objectives (Weinert et al., 2021). Multiple categories of MPAs exist[8], yet it often involves measures to counter "overexploitation of marine resources and degradation of marine habitats" such as a no-take area for fisheries (Weinert et al., 2021). Since

[6] Ørsted's Hornsea Project Two Offshore Wind Farm Decommissioning Programme, found at https://orstedcdn.azureedge.net/
[7] European Environmental Agency, at https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-protected-areas
[8] IUCN, at https://www.iucn.org/theme/protected-areas/about/protected-area-categories

OWFs are exclusion-zones during their operational period of circa 30 years, the designation of an MPA could be a practically feasible step (Ashley et al., 2014).

5.2. Decommissioning decision-making criteria

An overview of several wind and O&G decommissioning decision-making studies - provided in Appendix A- was used to identify frequently used criteria. In order to obtain a workable MCA analysis, a preliminary selection of these criteria was made based on expert input (ECHT, personal communication, 2021) and proposed to stakeholders during interviews. The criteria that received almost unanimous support were: decommissioning costs, opportunity costs for fisheries, material recycling benefits, liability costs, biodiversity change, protection potential, ocean access, and political compatibility. 'Recreational opportunities' was also considered as something interesting to investigate, though stakeholders were skeptical about its relevance. Other noteworthy feedback is as follows:

- Contrary to expectations, since Martins et al. (2020) had identified these as being key criteria, 'Safety of offshore personnel' and 'Technical feasibility' were not seen as beneficial to the analysis. Safety of offshore personnel was excluded, as all *Contractors* argued that they would only adopt safe practices anyway. Therefore, it is considered a precondition, rather than something to consider. Furthermore, all the examined alternatives are technologically possible according to *Contractors*. Nonetheless, they exhibit higher costs the more complex they are. As this is directly related to decommissioning costs, the criteria was considered redundant.
- Although 'Water quality' is highly applicable to the O&G industry due spill-risks, the criteria can be left out in offshore wind decommissioning decision making (*Sector association 1*). Additionally, Teunis et al., (2021), argues that potential chemical pollution of different strategies is expected to not significantly differ from one another. Therefore, the criteria was excluded.
- Both *eNGO 2* and *3* mentions that the spread of invasive species is a plausible threat of partial decommissioning, since these may be used as 'stepping stones' across the North Sea habitat. Nonetheless, Teunis et al (2021) mention that non-native species mainly inhabit the intertidal area of the structure (around sea level), hence not being relevant to the alternatives examined in this study. Yet, it does have to be monitored throughout the entire operational and decommissioning period to ensure risks will be kept low.

Lastly, despite the fact that the legal requirements regarding decommissioning are ultimately the all-decisive factor, a conscious decision was made to omit this legal criteria. In this way the advantages and disadvantages of the strategies can be examined, regardless of whether or not they are currently legally applicable. Resultingly, a selection has been made as shown in Table 5, in which criteria are divided over the triple-bottom-line categories to ensure a holistic overview.

Table 5. Final criteria selection divided over three categories and 10 criteria ('measurement unit' indicates how the criteria will be scored, 'desired output' indicates which direction of output is favored)

Category	Criteria	Definition	Measurement unit	Desired output
Economic profitability	Decommissioning cost	Estimated costs of the decommissioning process offshore that have to be spend by the Operator to successfully execute the proposed strategy, compared to baseline strategy (cutting below seabed)	Qualitative: substantially higher (++), higher (+), similar (+-), lower (-), substantially lower (--)	Low
	Opportunity costs: trawl 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 baseline strategy (cutting below seabed)	Euro's	Low
	Material recycling revenue	Estimated benefits from reusing or recycling the retained material from the monopile after successfully executing the proposed strategy.	Euro's	High
	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 seabed)	Qualitative: no residual liability (+-), only environmental or only safety liability (+), liability for both (++)	Low
Environmental impact	Biodiversity	The expected degree in biodiversity (i.e. species richness) after successfully executing the proposed strategy, compared to baseline strategy (cutting below seabed)	Qualitative: substantially higher (++), higher (+), similar (+-), lower (-), substantially lower (--)	High
	Protection potential	The area that is protected from anthropogenic habitat disturbances with conservation purposes after successfully executing the proposed strategy.	KM^2	High
	Habitat alteration	The expected degree of change in geomorphological characteristics of the benthic zone due to executing the proposed strategy compared baseline strategy (cutting below seabed)	Qualitative: similar habitat (+-), somewhat altered habitat (+), substantially altered habitat (++)	Low
Social acceptability	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.	Percentage accessibility based on number of ocean users granted access	High
	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 baseline strategy (cutting below seabed)	Qualitative: no difference in activities expected (+-), potential increase (+), potential substantial increase (++)	High
	Political compatibility	The expected governmental support for implementation of the proposed strategy, i.e. the suitability of the enabling environment.	Qualitative: 1 high, 0,5 medium, to 0 low support	High

5.3. Scoring of criteria

This section summarizes how the decommissioning alternatives score on the selected criteria, for which more detailed explanation per criteria and its underlying rationale is provided in Appendix B. The alternative 'below seabed removal' has been indicated as the baseline scenario to which the alternatives are compared, as this is the most likely decommissioning strategy to be implemented within the current legal framework in the Netherlands.

5.3.1. Economic profitability

Decommissioning costs

Estimations on foundation decommissioning costs are very scarce, especially at the level of detail examined in this study. Therefore, to assess this criteria, a qualitative score was provided based on literature and stakeholder statements (Table 6). The majority of monopile and scour decommissioning costs depend on the vessels required and their day-rates offshore (*Contractor 3*). Hence, it is expected that the most technologically difficult and therefore time-consuming practices will be the most expensive. Final scores are shown in Table 7 (detailed justification on page 55).

Table 6. Statements of stakeholders on Decommissioning costs

Stakeholder	Statement
Operator 1	*"It is much **cheaper to leave some of the foundations** in place than to get all of it up."*
Contractor 3	*"If you have to remove a complete monopile, you will need a ship with a heavier crane to lift the entire monopile. These do exist, but in general the larger ships with heavier cranes are more expensive. [...] The **day rate of ships is very decisive** in the dismantling activity."*
Contractor 4	*"Moving [of removed structures] is quite complex. Our preference would be to leave the scour, because we think that **removing the stones is really very difficult and costly**."*

Table 7. Scoring of Decommissioning costs compared to baseline (++ substantially higher, + higher, +- similar, - lower, -- substantially lower)

Alternative	**Complete removal**	**Below seabed removal**	**Topping**	**Topping + MPA**	**Scour left in situ**	**Scour left in situ + MPA**	**Designated reefing area**	Desired outcome
Decommissioning costs	++	+-	--	--	-	-	++	Low

Opportunity costs: trawl fisheries

The majority of the Dutch North Sea comes into contact with fisheries that use bottom-trawling (i.e. drag-nets) at least once a year (Teunis et al., 2021). Since OWFs are prohibited areas for these fisheries, some fishing grounds and consequently revenue are lost. The extent to which these revenues return after decommissioning will depend on whether the area is reopened and safely accessible for trawl-fisheries. The opportunity costs (i.e. revenue losses) are based on the total assumed OWF-induced losses for trawl-fisheries per year. In 2030, when OWFs will cover 1600 km^2, lost revenues are expected to be €1.52 million per year[9]. Converting this to the area

[9] The impact of offshore wind on fisheries, at https://windopzee.nl/onderwerpen-0/effect-op/activiteiten/visserij

of PAWP, a loss of €13.300 yearly for the 14 km^2 is found. Final scores are shown in Table 8 (detailed justification on page 55).

Table 8. Scoring of Opportunity costs: trawl-fishing

Alternative	Complete removal	Below seabed removal	Topping	Topping + MPA	Scour left in situ	Scour left in situ + MPA	Designated reefing area	Desired outcome
Opportunity costs: trawl fishing	€0	€0	€1000	€13300	€0	€13300	€950	Low

Monopile recycling revenue

Although several ideas exist on the recycling of scour protection, this is still very hypothetical (Fortune & Paterson, 2020). This study therefore focuses on steel recycling, since this is deemed certain and profitable in the future as it is used in large quantities and relatively easy to recycle (Gokhale, 2020). Scores are based on an estimated market value of €300 per tons steel and a recycling rate of 95% (TNO, 2020). PAWP's monopiles are 54 meters long and contain 320 tons of steel each (Vanagt & Faasse, 2014). This means that if no steel is lost during recycling, €96000 can be earned. Calculations are shown in Table 9 (detailed justification on page 56).

Table 9. Steel recycling revenue calculations

Alternative	Complete removal	Below seabed removal	Topping	Topping + MPA	Scour left in situ	Scour left in situ + MPA	Designated reefing area
Monopile collected (in m)	54	33.5	27	27	33.5	33.5	0
Weight collected (in tons)	320	198,52	160	160	198,52	198,52	0
Weight recycled (in tons)	304	188,59	152	152	188,59	188,59	0
Value obtained (€)	**91200**	**56.578,2**	**45.600**	**45.600**	**56.578,2**	**56.578,2**	**0**

Residual liability costs

If abandonment of leaving structures on the seabed is approved, an obligation of monitoring and maintenance of the structures towards the departing operator remains (*Govt* 2). Operators must verify on a regularly basis that the structure left behind remains in a safe and reliable condition (*Govt 2*). Moreover, OWF operators are likely to remain fully liable for any safety consequences (Fowler et al., 2020). The assessment of this criteria is based on available literature and stakeholder input (Table 10). The higher the risk of environmental and/or safety hazards of an alternative, the higher its score. Final scores are shown in Table 11 (detailed justification on page 57).

Table 10. Statement of stakeholder on Liability within MPA

Stakeholder	Statement
eNGO 3	*"It depends on what you want to leave behind, if it's only the stone scour base, then it's a completely different story than if you also leave something of the structure behind. Because then you get into all these **safety issues**."*
Govt 3	*"If a fishing boat gets stuck, it will simply capsize the boat, which is life-threatening […]. So then you start to pose real risks, so you really have to find a **way of balancing that risk**. Maybe **leaving the scour protection** in place **and removing the monopiles** is one way of doing that."*
Govt 2	***"If there exists a no-go zone** in that area, I can't imagine that the government is liable for [any damage or safety issues], nor the company that once had the license for the OWF. Then [any damage or safety issues] are [the shipper's] **own responsibility**. I make a comparison with a safety zone around an operational OWF; if you accidentally hit a valve there or you capsize because you've hit the ground and get stuck behind something, then it's really your own fault."*

Table 11. Scoring of Residual liability costs (+- no residual liability, + only environmental or only safety liability, ++ liability for both)

Alternative	Complete removal	Below seabed removal	Topping	Topping + MPA	Scour left in situ	Scour left in situ + MPA	Designated reefing area	Desired outcome
Residual liability costs	+-	+-	++	+-	+	+-	+-	Low

5.3.2. Environmental impact

Biodiversity

Scoring of this criteria is based on two assumptions: the more complex the habitat is, the higher the biodiversity will be due to creation of specific niches in which different species can thrive (*Ecologist 1,* Fortune & Paterson, 2020); and the less habitat disturbance, the higher the biodiversity (Teunis et al., 2021). Accordingly, alternatives that provide the most habitat complexity and which are protected from habitat disturbance, will show the highest rates of biodiversity. Scores are shown in Table 12 (detailed justification on page 57). Moreover, recovery rates to a pre-OWF environment will depend multiple factors, including further benthic disturbance (Fortune & Paterson, 2020).

Table 12. Scoring of Biodiversity compared to baseline (++ substantially higher, + higher, +- similar, - lower, -- substantially lower)

Alternative	Complete removal	Below seabed removal	Topping	Topping + MPA	Scour left in situ	Scour left in situ + MPA	Designated reefing area	Desired outcome
Biodiversity change	+-	+-	+	++	+-	+	++	High

Natural habitat alteration

As is strongly emphasized by eNGOs, the *original* state of the environment pre-OWF is also a highly important environmental factor that should be taken into account (*eNGO 2* and *3*). From this perspective, leaving structures in situ is regarded as marine littering, thereby altering the environment towards unnatural habitats. For this criteria, alternatives are scored based on this perspective of recovery of 'naturalness', for which provided scores are shown in Table 13 (more detailed justification on page 59).

Table 13. Scoring of Habitat alteration compared to baseline (+- similar habitat, + somewhat altered habitat, ++ substantially altered habitat)

Alternative	**Complete removal**	**Below seabed removal**	**Topping**	**Topping + MPA**	**Scour left in situ**	**Scour left in situ + MPA**	**Designated reefing area**	Desired outcome
Habitat alteration	+-	+-	++	++	+	+	++	Low

Protection potential

Since OWFs already act as de-facto MPAs, alternatives that result in maintaining a certain level of exclusion after decommissioning, albeit directly (MPA implementation) or indirectly (vessels avoiding structures due to safety risks), can contribute to further nature protection within the area (Sommer et al., 2019) (Table 14). Heavy shipping and fisheries are expected to be inconvenienced by a 2-metre protruding monopile, but not by the scour left behind (*Govt 2*). Final scores are shown in Table 15 (detailed justification on page 59).

Table 14. Statements of stakeholders on Protection potential

Stakeholder	**Statement**
Operator 2	*"As bottom trawling is not possible, it is of course also possible to* ***recover those biogenic reefs****"*
Govt 2	*"A large vessel is not allowed to pass through [an OWF], because it is obliged to keep to these routes, and those routes are always around [an OWF]. So the habitat is* ***indirectly protected****"*

Table 15. Scoring of Protection potential

Alternative	**Complete removal**	**Below seabed removal**	**Topping**	**Topping + MPA**	**Scour left in situ**	**Scour left in situ + MPA**	**Designated reefing area**	Desired outcome
Protection potential	0 km^2	0 km^2	1 km^2	14 km^2	0 km^2	14 km^2	1 km^2	High

5.3.3. Social acceptability

Ocean access

When an OWF-permit expires after 30 years, the best new use for the area is reviewed (*Govt 2*). The Dutch North Sea is one of the most intensively used marine areas in the world[10]. Ideally, as many users of the sea as possible

[10] Rijkwaterstaat, at https://www.rijkswaterstaat.nl/water/vaarwegenoverzicht/noordzee

should regain access to the site, especially users of the activities of national interest (Kerkvliet & Polatidis, 2016), *Govt 2*). Current activities of national importance as designated by the Dutch government are shipping, sand extraction for sand replenishment, O&G extraction, wind energy generation, CO2-storage and military exercises[11]. Fisheries nor nature conservation are activities of national interest (*Govt 2*). This criteria is scored based on the level of accessibility to the decommissioned area by these activities of national importance. Scores are shown in (detailed justification on page 59).

Table 16. Scoring of Ocean access

Alternative	Complete removal	Below seabed removal	Topping	Topping + MPA	Scour left in situ	Scour left in situ + MPA	Designated reefing area	Desired outcome
Ocean access	100%	67%	50%	17%	67%	17%	67%	High

Recreational opportunities

Apart from activities of national importance, commercial fisheries and nature preservation, the Dutch North Sea is also used for recreational activities such as recreational fishing, vessels, and diving. Partially decommissioned OWFs may have value as tourism hotspots, as is also argued for O&G structures (Henrion et al., 2015). Firstly, due to the expected increase in biomass and biodiversity within OWFs, recreational fishing opportunities get more attractive (*Ecologist 1*). In addition, biodiversity hotspots may become interesting dive sites. Higher scores are awarded the more recreational activities (diving, sailing and/or fishing) are expected to be positively influenced by the proposed decommissioning strategy. Scores are shown in Table 17 (detailed justification on page 60).

Table 17. Scoring of Recreational opportunities compared to baseline (+- no difference in activities, + potential increase, ++ potential substantial increase)

Alternative	Complete removal	Below seabed removal	Topping	Topping + MPA	Scour left in situ	Scour left in situ + MPA	Designated reefing area	Desired outcome
Recreational opportunities	+-	+-	+	++	+-	++	++	High

Political compatibility

In the 10-tenets framework, a marine management approach is assumed to be politically expedient if the support of political leaders is assured and if the approach is consistent with the prevailing political environment (Smyth et al., 2015). To estimate the political expediency, government parties were interviewed, from which three guiding statements were drawn and evaluated against the alternatives (Table 18, detailed justification on page 61):

[11] North Sea management, at https://www.noordzeeloket.nl/beheer/

1. **Multi-use**. Due to the high value of other economic and infrastructural activities at sea, and because the value of nature is not (yet) considered sufficiently high, policy makers will not quickly assign an area *exclusively* for nature conservation in North Sea spatial planning (*Govt 2)*.
2. **Clearance**. Based on international and national legal regulations to which authorities must currently obey, considerable support is expected for seabed clearing. However, if anything is permitted to be left behind, more support is expected for leaving just scour in situ, rather than steel (*Govt 3*).
3. **Safety**. In case there are any safety risks for other sea users, an approach is unlikely to show political support (*Consultant 2*). Consequently, leaving structures behind without clear nautical markings receive lower scores.

Table 18. Scoring of alternatives on Political compatibility (1 high, 0,5 medium, to 0 low support)

Alternative	Complete removal	Below seabed removal	Topping	Topping + MPA	Scour left in situ	Scour left in situ + MPA	Designated reefing area
Multi-use	1	1	0,5	0	1	0	1
Clearance	1	1	0	0	0,5	0,5	0,5
Safety	1	1	0	1	1	1	1
Total score	**3**	**3**	**0,5**	**1**	**2,5**	**1,5**	**2,5**

5.3.4. Summary of scores

Table 19. Effects table with scores and standardized scores

Sub-criteria	Measurement unit	Complete removal		Below seabed removal		Topping		Topping + MPA		Scour left in situ		Scour left in situ + MPA		Designated reefing area	
		Score	Standardized	Score	Standardized	Score	Standardized	Score	Standardized	Score	Standardized	Score	Standardized	Score	Standardized
Decommissioning costs	Qualitative: substantially higher (++), higher (+), similar (+-), lower (-), substantially lower (--)	++	0,00	+-	0,33	--	1,00	--	1,00	-	0,67	-	0,67	++	0,00
Opportunity costs: trawl fishing	Euro's	0	1,00	0	1,00	1000	0,92	13300	0,92	0	1,00	13300	0,00	950	0,93
Material recycling revenue	Euro's	91200	1,00	56.578,2	0,62	45.600	0,50	45.600	0,50	56.578,2	0,62	56.578,2	0,62	0	0,00
Residual liability costs	Qualitative: no residual liability (+-), only environmental or only safety liability (+), liability for both (++)	+-	1,00	+-	1,00	++	0,00	+-	0,00	+	0,50	+-	1,00	+-	1,00
Biodiversity	Qualitative: substantially higher (++), higher (+), similar (+-), lower (-), substantially lower (--)	+-	0,00	+-	0,00	+	0,50	++	1,00	+-	0,50	+	0,50	++	1,00
Habitat alteration	Qualitative: similar habitat (+-), somewhat altered habitat (+), substantially altered habitat (++)	+-	0,00	+-	0,00	++	0,07	++	0,07	+	0,00	+	1,00	++	0,07
Protection potential	KM^2	0	1,00	0	1,00	1	0,00	14	0,00	0	0,50	14	0,50	1	0,00
Ocean access	Percentage accessibility based on number of ocean users granted access	100	1,00	67	0,67	50	0,50	17	0,50	67	0,67	17	0,17	67	0,67
Recreational opportunities	Qualitative: no difference in activities expected (+-), potential increase (+), potential substantial increase (++)	+-	0,00	+-	0,00	+	0,50	++	0,50	+-	0,50	++	1,00	++	1,00
Political compatibility	Qualitative: 1 high, 0,5 medium, to 0 low support	3	1,00	3	1,00	0,5	0,17	1	0,17	2,5	0,83	1,5	0,50	2,5	0,83

5.4. Stakeholder weighting

A total of 13 stakeholders responded to the request to appoint relative importance to the selected criteria, missing only representation from the Fisheries group. Therefore, for Fisheries a hypothetical weighting was defined based on interviews: the fishing industry wants as many 'unobstructed' (i.e. fishable) grounds as possible; higher biodiversity is beneficial; and abandoned structures need to be closely monitored for safety. Accordingly, trawl-fishing opportunity costs is weighted heaviest for this group, followed by ocean access, biodiversity, and residual liability costs.

In reality, particular stakeholders are expected to have more leverage in decommissioning decision-making. Therefore, calculating the combined weights per criteria as an average weight of all stakeholders is not realistic. Expert consultation was conducted to estimate relative importance of stakeholders' on the decommissioning process. The lowest to highest degree of influence emerged as follows (ECHT, personal communication, 2021), also stating respective assigned importance in the combined-weighting calculations:

- Government (through policy and legislative governance) weights are counted in 6 times
- Operators (as a regulatory party within wind industry) weights are counted in 5 times
- Contractors weights (as an executive party of the decommissioning process) are counted in 4 times
- eNGOs (through image creation and lobbying) weights are counted in 3 times
- Environmental experts, i.e. ecologists and consultants (through advancing scientific knowledge) weights are counted in 2 times
- Fisheries (cultural image yet low economic impact) weights are counted in once

Results of individual and combined weights are shown in Figure 8. For combined-weighting, the category economic profitability has overall highest value, closely followed by environmental impact, while social acceptability receives far less importance. As for the criteria, cost effectiveness, residual liability costs and protection potential are valued highest in the combined-weighting. By far the least valued criteria is recreational opportunities. For stakeholders, the weighting varies a lot, but a large overlap is the low weighted social acceptability category. For marine environmental experts, economic profitability scores significantly low, which contrasts with the high weight given to this category by Contractors and Fisheries. Not surprisingly, for Operators and Contractors, the decommissioning costs criteria scores highest.

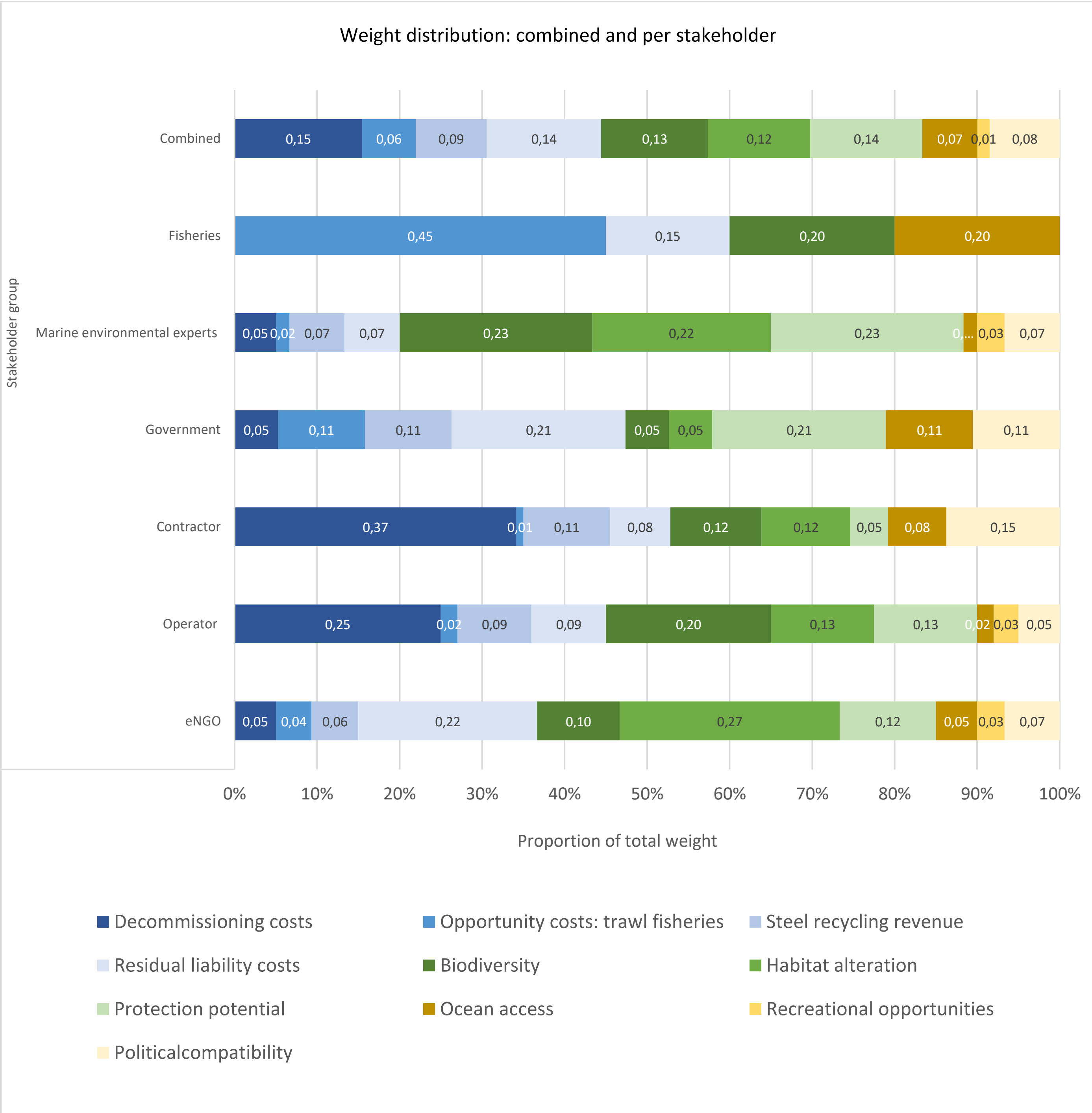

Figure 8. Overview of combined weighting of all stakeholders (based on proportional influence in the decommissioning decision-making process) and average weights per stakeholder group. Blue shades indicate economic profitability criteria, green indicates environmental impact criteria and yellow indicates social acceptability criteria.

6. Results

This chapter discusses the results of the MCA. Figure 9 shows the results of scoring, weighting and ranking the alternatives with combined weight, while the graphs in Figure 10 show scores per stakeholder group. These results are elaborated on in three steps: a sensitivity analysis to check the robustness of the framework, analysis of differences between criteria, and analysis of differences among stakeholders.

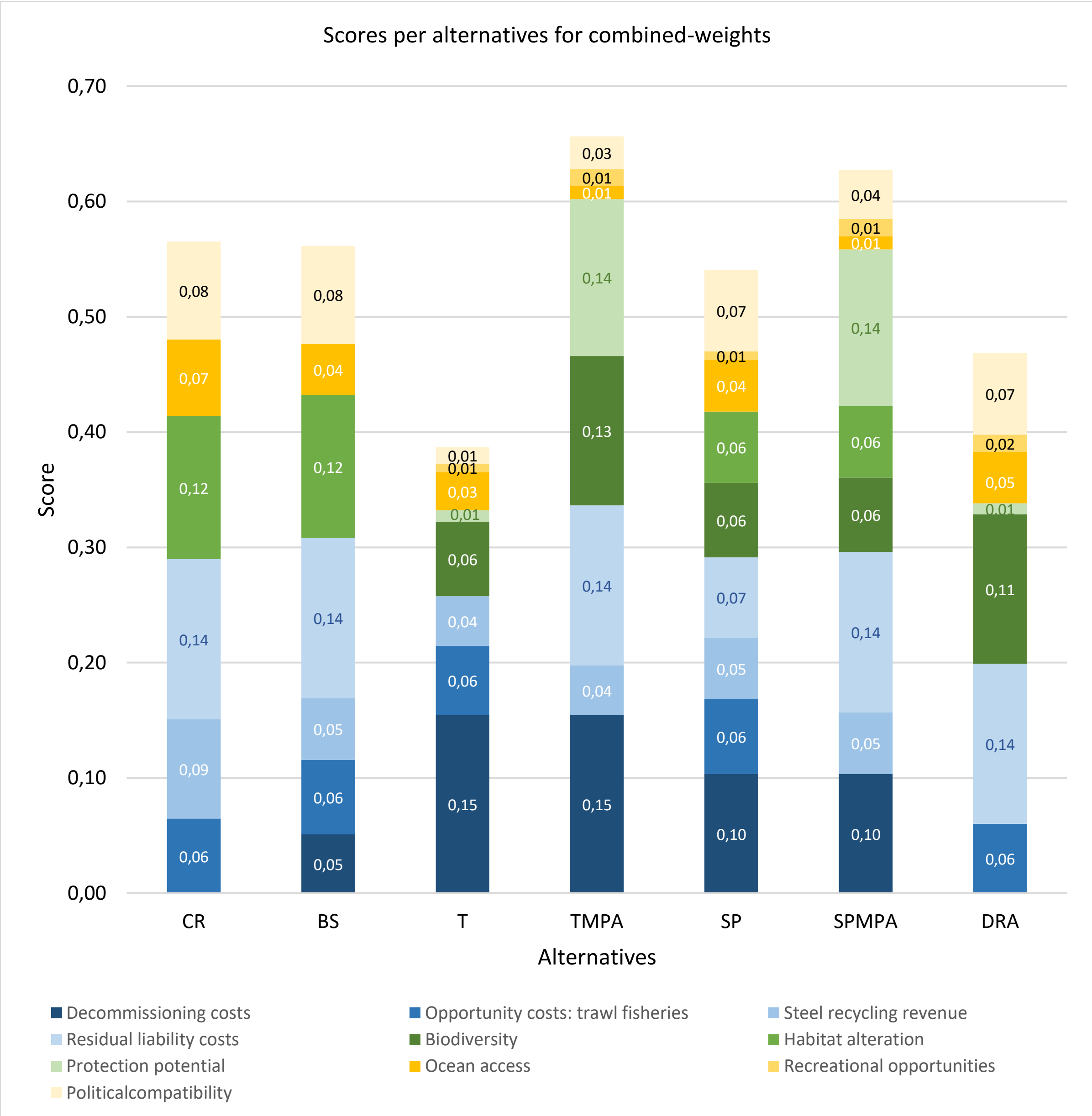

Figure 9. Final scores based on combined-weights per decommissioning alternative: Complete Removal, Below Seabed removal, Topping, Topping + MPA, Scour left in situ, Scour left in situ + MPA, and Designated Reefing Area. Blue shades indicate economic profitability criteria, green indicates environmental impact criteria and yellow indicates social acceptability criteria

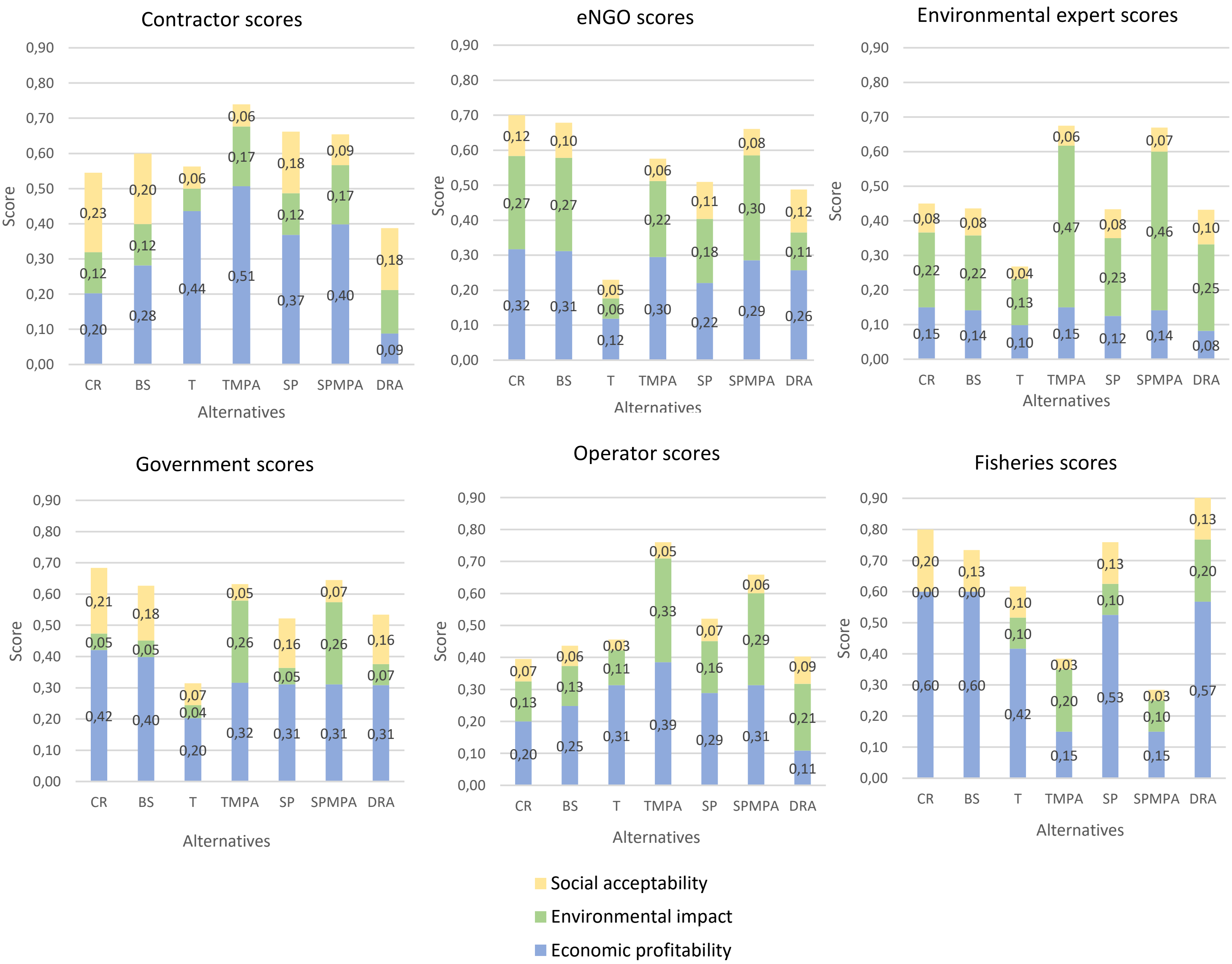

Figure 10. Final scores of alternatives per stakeholder group per decommissioning alternative: Complete Removal, Below Seabed removal, Topping, Topping + MPA, Scour left in situ, Scour left in situ + MPA, and Designated Reefing Area.

6.1.1. Comparison between alternatives

Several noteworthy differences between alternatives can be observed. Firstly, MPA-alternatives, ranking both first and second, score significantly higher than their non-MPA counterparts and show the most environmental benefit out of all alternatives. This is due to their high protection potential, which is a heavily weighted criteria among stakeholders. Interestingly however, MPA-alternatives score lowest on the social acceptability category, along with Topping, and especially low on the criteria political compatibility. The alternative that shows the highest score for the category social acceptability is complete removal (CR), closely followed by below seabed removal (BS), Designated Reefing Area (DRA) and only scour left in situ (SP). All these alternatives do show little or no protection potential, which indicates a trade-offs between social acceptability and protection potential.

Moreover, in addition to its low social acceptability, Topping scores least favorable for the environmental category. The alternative provides no further protection potential and unnatural steel is abandoned in situ. Also economic profitability is low for Topping, which is surprising due to its advantageous decommissioning costs. Yet high liability issues seem to outweigh this financial benefit. Since Topping scores low for economic, environmental and social criteria, it is not surprising this is the least preferrable alternative. Interestingly however, in combination with MPA (TMPA), the provides the highest score for both economic profitability and environmental benefits among all alternatives. This suggests that the implementation of MPAs is critical to its success.

Lastly, scour left in situ with MPA implementation (SPMPA) scores highest for the environmental category and is simultaneously the only alternative that provides at least some benefit for all the environmental criteria. For example, in BS and CR only seabed clearance is provided, while for TMPA, Topping and DRA, this is actually the only benefit that is missing. Moreover, only leaving scour in situ (SP) provides some degree of seabed clearance and biodiversity benefit, yet is not protected for further habitat disturbance. These findings indicate a wide variation in the combination of environmental benefits provided by each alternative. For the economic and social criteria, this seems more evenly spread out among alternatives.

6.1.2. Comparison between stakeholders

In several cases, the combined-weight ranking is similar to that of individual stakeholders, such as for Contractors and Environmental experts, and in some extent to eNGOs and Government. This could indicate broad support if choices are made based on the combined-weights ranking. Very interesting to note is that even though the rankings sometimes appear similar, the composition of the criteria that determine these rankings varies by stakeholder. For example, TMPA ranks highest for Contractors, Environmental experts and Operators. Yet for Contractors, economic profitability clearly contributes most, while for Environmental experts, the environmental impact category is most dominant. For Operators, there seems to be a balance between these categories. Another example is the almost identical ranking of Government and eNGOs, yet for eNGOs the environmental category is dominant, while for Government especially economic profitability dominates. Concluding, even though stakeholders have different interests, similar decommissioning alternatives may be preferred.

But despite much overlap, a contrast is found as well. This contrast becomes clearer in Table 20, whichs shows a visualisation of the scores of each stakeholder groups by means of a color-coded scheme. A challenging position of Fisheries' preferences to those of other stakeholders is noticable. For example, for TMPA and SPMPA, the first and second highest ranked in combined-weight, fisheries show the least advantage over their preferences. Contrastingly, in the case of DRA, which shows low scores for all other stakeholders, Fisheries actually have their highest score. These findings seem to indicate that fisheries in their most sought-after options, suffer their biggest losses, and vice versa.

Table 20. Color scheme of scores per alternative for individual stakeholder groups

Stakeholder	Complete removal	Below seabed removal	Topping	Topping + MPA	Scour left in situ	Scour left in situ + MPA	Designated reefing area
Government	0,68	0,63	0,31	0,63	0,52	0,64	0,53
Operator	0,40	0,44	0,46	0,76	0,52	0,66	0,40
Contractor	0,55	0,60	0,56	0,74	0,66	0,65	0,39
eNGO	0,70	0,68	0,23	0,58	0,51	0,66	0,49
Envir. experts	0,45	0,44	0,27	0,68	0,43	0,67	0,43
Fisheries	0,80	0,73	0,62	0,38	0,76	0,28	0,90

>0,75
>0,65
>0,55
>0,45
>0,35
<0,35

6.1.3. Sensitivity analysis

Before discussing these results, the robustness of the framework was examined by conducting several sensitivity- and scenario-analyses (Appendix C). Firstly, it was evaluated whether the hypothetical fisheries weights affected the outcome significantly. No substantial changes in rankings or alternative scores were found when excluding Fisheries weights. Rather than deciding to exclude Fisheries weights in the framework for this reason, they were retained to maintain some degree of representativeness for this group of stakeholders. Nevertheless, they should be interpreted with caution.

Second, because great assumptions are involved in scoring the decommissioning costs, which is the heaviest weighted criteria, the framework was tested on two scenarios: cost-effective complete removal and cost-effective designated reefing area. The cost-effective complete removal scenario-analysis shows that the alternatives becomes clearly highest in rank when changing its score to both lower (-) as well as substantially lower (--) costs. The development of cost-effective complete removal therefore has great impact on decommissioning decision-making, hence developments needs to be closely monitored. For example, the Hydraulic Pile Extraction Scale Tests (HyPE-ST) project is currently researching how to entirely extract a monopile more efficiently[12]. Contrastingly, the ranking remains the same in the cost-effective DRA scenario-analysis. Cost-effective DRA could occur through establishing a DRA close to the OWF, thereby reducing technical difficulties and vessel time. Therefore, under current conditions, DRA does not appear to be an appealing decommissioning alternative.

Lastly, three general sensitivity analyses were conducted: equalizing all weights, extreme weighting for environmental criteria, and extreme weighting for social criteria. It was concluded that the framework is very robust to changes in weighting. It is therefore argued that MCA outcomes are resilient to assumptions and guesses made by stakeholders in the weighting process.

[12] HyPE-ST project, at https://www.deltares.nl/en/projects/sustainable-decommissioning-offshore-wind-turbine-foundations/

7. Discussion

In this section, the results are further reviewed and discussed in relation to stakeholder statements and the literature. The discussion is based on two main themes that emerged during the analysis of the role of nature in decommissioning decision-making: the potential of Marine Protected Areas (MPAs) and trade-offs between environmental criteria. In addition, the importance of liability costs is elaborated on. Based on these discussion points, policy recommendations are ultimately formulated.

7.1.1. Marine protected areas: benefit or hinder?

MPA-alternatives rank highest with combined-weights, which can be deduced from their cost-effectiveness, high protection potential, and low residual liability costs compared to other alternatives. Their high ranking is therefore not very surprising, since these criteria all received heavy weights. Even for Fisheries, for which MPA-alternatives score relatively low, these strategies are considered beneficial to some extent (*Fisheries 1*). This is because the fishing industry is already accustomed to the exclusion zone in this area, thereby minimizing the inconvenience of closing areas elsewhere. However, whether MPA alternatives are actually implementable, depends on multiple factors. Several stakeholder statements on this are shown in Table 21, which are elaborated on further.

First, the true benefit of implementing MPAs is debatable. On the one hand, OWFs may not be considered valuable enough for nature conservation (*Govt 2*, *Govt 3, eNGO 3*). *eNGO 3* expresses concerns that considering decommissioned OWFs as MPAs could even undermine the ambition to protect other valuable marine habitats, such as the *Bruine bank*[13], up to the 30% protection target set by the EU. Nonetheless, *Operator 2* and *Govt 1* state that the exclusion of bottom-disturbing activities may have actually made this area valuable enough to protect in the period it has been operational. Also, *Fishery 1* argued that given the discussions about the artificial reef effects in OWFs, the argument of not showing sufficient nature value is rather contradictory. Therefore, the concept of what is *valuable enough* to protect should be carefully considered and consulted upon.

The second aspect causing uncertain support for MPA implementation, is the user pressure on the North Sea. Both political compatibility and ocean access both score low for MPA alternatives. Although it is already taken into account by the stakeholder weighting, governmental authorities will have the final say in the decommissioning decision-process through their position in the regulatory enabling environment. As marine nature conservation is not an activity of national importance (*Govt 2, Operator 2*), closing off areas as MPAs is challenging, despite them offering potentially economically and environmentally desirable alternatives.

To test whether strengthened governmental conservation objectives would change the MCA outcome, a scenario-analysis is conducted (Figure 11). The results indicate that only MPA-alternatives become more attractive, while all other alternatives get far less attractive, including partial removal strategies. For this reason,

[13] Draft decision protection area Bruine Bank https://www.natura2000.nl/nieuws/ontwerpbesluit-bruine-bank-ter-inzage-tm-4-mei-2021

MPA alternatives should be taken into account even more seriously when national conservation objectives get strengthened.

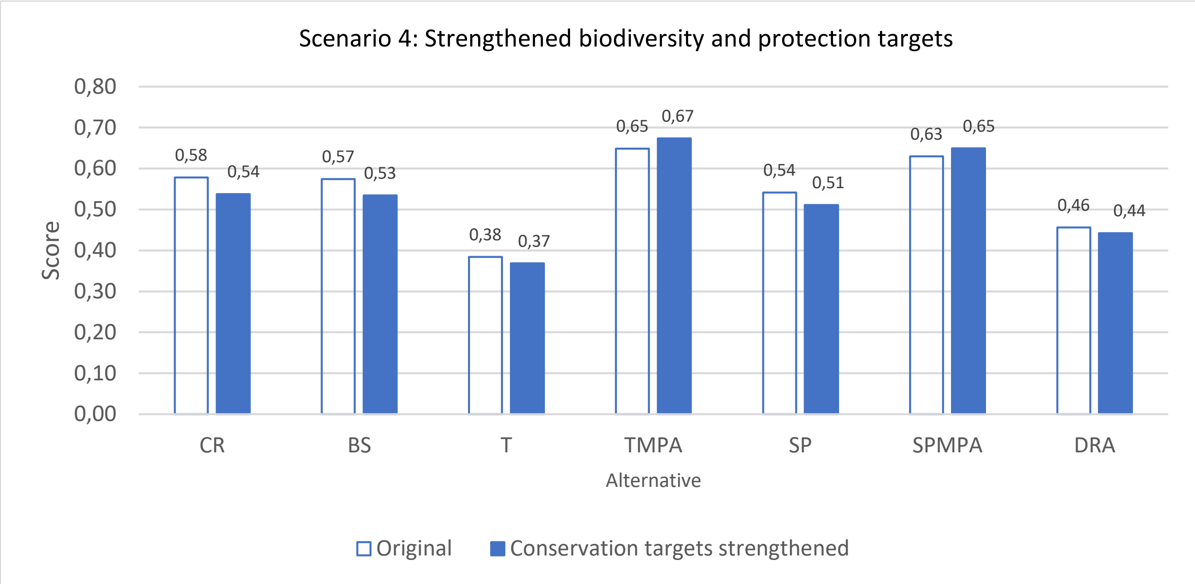

Figure 11. Scenario-analysis of strengthened biodiversity and conservation potential criteria importance (doubled in weight) by stakeholder group Government

Table 21. Statements of stakeholders on Marine Protected Areas

Stakeholder	Statement
Govt 2	*"To protect parts of the seabed from bottom trawling in particular, you also have to* ***designate the best areas*** *for this. And these are not always the wind farms."*
eNGO 3	*"My personal experience is not that the government is "adding" [protected area within OWFs] to the actual nature reserves. […] This would be* ***nice as an extra, but not as a replacement for the 30%."***
Fisheries 1	*"On the one hand, everyone says, well, a wind farm is a refugium and a beautiful environmental area, etcetera. But if you then propose, well, we are going to designate it as a protected area too, then suddenly everyone has* ***all sorts of problems****."*
Govt 3	*"In Europe there are guidelines, which the Dutch government has to follow: 30% of North Sea should be protected, among other things against fishing. But there are a number of questions: which nature has actually been formed there****, is this nature valuable****, and do we want to leave it?"*
Govt 1	*"There can indeed be a decision to protect those areas where* ***development may have started anyway****, because they have been protected for 25 years, free from bottom trawling."*
Govt 2	*"With the* ***current use of space*** *in the North Sea, the establishment of MPAs seems unlikely: at present, restoration of nature is not as valuable for the Netherlands as other uses".*
Operator 2	*"[MPAs] are also an option to be explored. But with the* ***current use of space*** *and when I see how people are lobbying for joint use of wind farms, I don't know how realistic it is."*

7.1.2. Diversity versus Naturalness

Below seabed removal (BS) and complete removal (CR) both rank moderately high in combined-weight ranking, third and fourth respectively. The only environmental benefit they provide is clearing the seabed, not increasing biodiversity nor protection from further disturbance. However, among stakeholders the assumptions about and the advantages of returning to natural nature appear highly controversial. A number of arguments that display this discord among stakeholders are shown in Table 22 and discussed further.

Leaving behind structures is considered an opportunity to protect the area from soil-disturbing activities (*Ecologist 1*) and recover hard substrate habitats (*Consultant 1*), and thereby conservate marine nature (*Operator 1*). Also in literature, arguments against returning to pre-OWF conditions are mentioned. Fortune & Paterson (2020) argue that full recovery may take over decades, Smyth et al. (2014) even argue that the marine environment may not recover to its original state at all, after exposure to construction and decommissioning activities. Moreover, abandoning structures may also create a *blue nature corridor*, meaning that connectivity between nature areas in the North Sea is in this way established, thereby strengthening their ecological stability (*Govt 2)*. For OWFs in particular, Vanagt & Faasse (2014) argue that species populations are more resilient to local impacts because recovery rates are higher than for individual shipwrecks and O&G platforms since they cover larger areas. This could stabilize and protect the North Sea ecology. Concluding, recovering pre-OWF conditions might not always be environmentally desirable.

On the other hand, stakeholders express negative or skeptical attitudes towards leaving structures on the seabed, for which their argument is twofold. Firstly, the risk of a *precedent effect* is expressed, which indicates that the abandonment of one structure, may lead to other structures also being more easily abandoned by other parties under the guise of artificial reef (*eNGO 2* and *3*). Although precedent effect could be avoided by case-by-case consideration of all instances, an approach as advised in Fowler et al., (2020), such an approach might lower the jurisdictional barrier so severely that it becomes too easy for the industry to find a reason to abandon it every time (*eNGO* 2). Despite some hard substrate might be beneficial, the Dutch North Sea was never completely filled with boulders (*Consultant 1, Operator 2)*. Moreover, the North Sea species under pressure are not necessarily the ones that benefit from hard substrate increases (van Duren et al., 2016). Similarly, *Govt 1* states that an increase in biodiversity may not be desirable if it is not inherent to that particular ecosystem. Concluding, leaving behind all substrates that improve some sort of artificial reef effect is disproportional, and one must be careful in permitting the abandonment of structures (van Duren et al., 2016).

Secondly, one can speak of *artificial reefs of convenience* (*eNGO 2).* This means that partial removal may only be promoted as environmentally beneficial due to lower accompanied decommissioning costs, which may indicate greenwashing (*eNGO 2*). This cautionary attitude is consistent with ongoing tensions in the O&G industry, where 'Rigs-to-Reefs' programs -which proposed partial decommissioning strategies- were often put away as greenwashing (Fowler et al., 2014).

For solving greenwashing claims, it was proposed to invest cost-savings into marine nature protection or enhancement measures (*O&G 1, Ecologist 1)*. In that case, abandonment of structures does not result in cost-savings for the industry anymore and thus cannot be labeled as greenwashing. In this scenario, when decommissioning costs of all removal alternatives become similar, the results are as shown in Figure 12. In this case, below seabed removal, complete removal and scour in place with MPA implementation rank almost identical. These results suggest that SPMPA continues to be beneficial and in this scenario may even provide hard substrate restoration, protection potential, and investment in nature elsewhere.

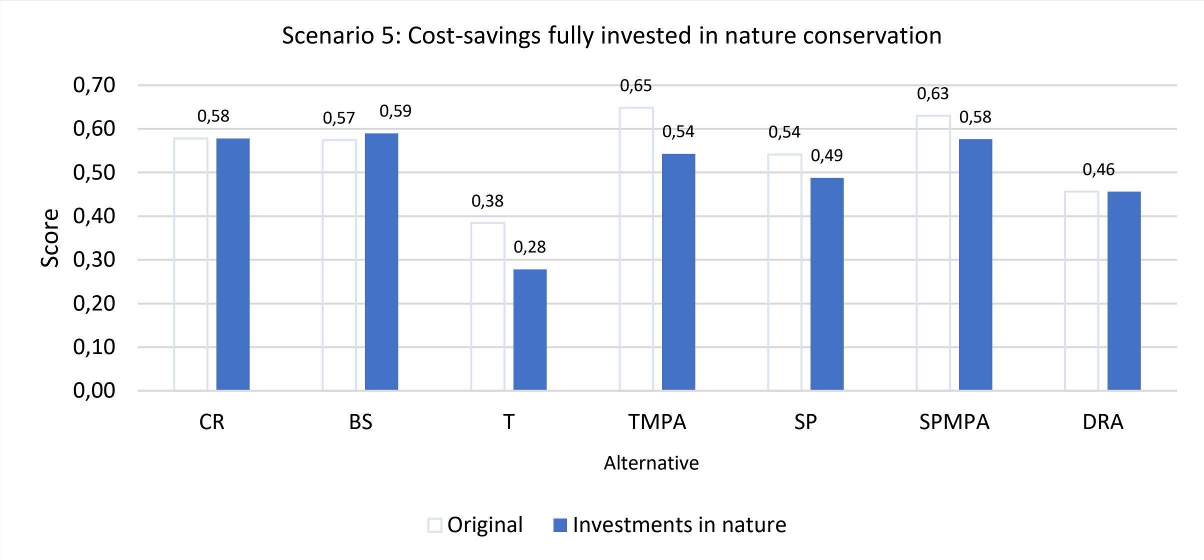

Figure 12. Scenario-analysis of scenario in which reduced costs compared to below seabed cutting are fully invested in nature conservation

Table 22. Statements of stakeholders on Naturalness versus Biodiversity

Stakeholder	Statement
Ecologist 1	*"I see [leaving structures] as an* ***enrichment****. With all the disclaimers that this is about clean steel, not all kinds of coatings."*
Consultant 2	*"From an ecological point of view, it is* ***good to leave scour****."*
Govt 2	*"Provided that we all consider them important enough and that if you choose the right spots -OWEZ for example is a really nice spot because it's close to the coast- it could* ***meet the need to keep the connection*** *between valuable [nature reserves]"*
Operator 1	*"In the short-term it is absolutely* ***best for marine life to leave the structures*** *there. No question. But it is* ***less natural than*** *removing them."*
Govt 2	*"There is a* ***difference between excluding negative effects and throwing things into the North Sea*** *that don't originally belong there"*
Govt 1	*"If you start adding [hard substrates] on a very large scale to where it does not naturally occur, then you add biodiversity, but it is just like suddenly adding rose bushes and tulips to a natural forest.* ***It looks nice, but it doesn't belong there.****"*
eNGO 2	*"It can be very difficult sometimes to define what is natural. When you have an area that has been trawled over for so many decades,* ***what is natural*** *in that case?"*
eNGO 2	*"We tend to assume that more species […] are good for the marine environment. I think we have to look at how close what we leave behind is to the natural system that is there, and had been there. My*

	experience is that the marine environment thrives best when we leave it alone and ***give it as much chance as possible to recover naturally****."*
eNGO 2	*"If you allow for more generic decisions to be taken, and you start redefining things as artificial reefs rather than designing them as such, you open the door for much less scrutiny, much more opportunity for things* ***just to be left behind of convenience****. […] Then it would be very easy to argue in every situation that there are things growing on the structures so therefore you should have to leave it."*
Consultant 1	*"On the one hand, it is a reasonable argument to say: quite a bit of hard substrate has disappeared from the North Sea […] but on the other hand: the North Sea* ***has never been one big rock pool****."*

7.1.3. Residual liability costs

Liability costs are often regarded as the strongest disincentive for the abandonment of offshore structures, both in literature (Schroeder & Love; Fowler et al., 2020) as well as interviews (Table 23). This conception is likely a remnant from the O&G industry, where despite well-founded counter-arguments, residual liability costs often led to complete removal (Fowler et al., 2015). Nonetheless, several findings suggest that the effect of residual liability is being overestimated.

Firstly, as argued by Schroeder & Love (2004) for O&G, when the structures left in situ are clearly marked by buoys and warnings on nautical maps, liability for any incidents is not expected to lie with the departing permit-holder. Correspondingly, *Govt 2* argues that in such cases not the government nor the departing party are responsible for any occurring damage. This may explain why Operators, the very stakeholder group who has to bear these costs, do not give this criterion exceptional weight.

Moreover, when comparing OWFs to the O&G industry, monitoring and maintenance costs are anticipated to be significantly lower. No major risks, such as chemical spills, are namely expected (*Govt 2*). Additionally, scour has a somewhat natural and seemingly safe character (*Govt 2, Govt 3, eNGO 3*). This indicates that residual liability for wind should be approached in a different way than in O&G.

Provided that proper nautical markings can be maintained, all alternatives could consequently result in low liability costs. The results of such a scenario are shown in Figure 13. Apart from the fact that Topping and SP become slightly more attractive alternatives, no major changes are observed in the overall ranking. TMPA and SPMPA remain highest in rank, followed by CR and BS. Concluding, despite the fact that the enforcement costs associated with the required nautical designations (buoys and on nautical charts) can also be costly, residual liability costs may not have as great an impact on the preferred decommissioning strategy as expected.

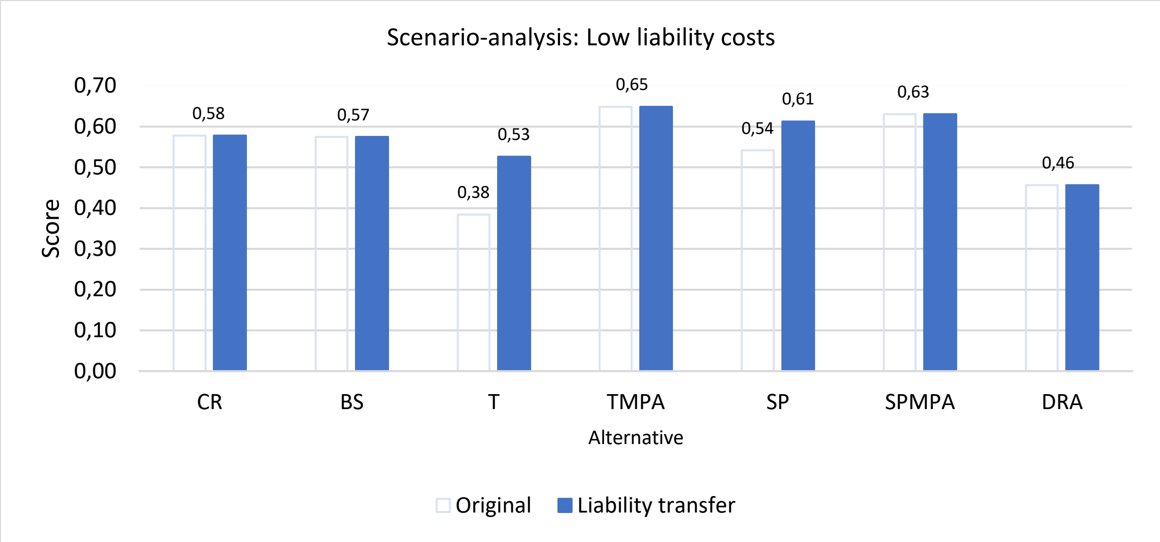

Figure 13. Scenario analysis where liability to the departing permit-holder are the same for all alternatives (+-)

Table 23. Statements of stakeholders on Liability issues

Stakeholder	Statement
Operator 1	*'I guess for [leaving structures on the seabed] to be attractive option, it would need to be a clear, closed case. That our **responsibility as a wind farm developer ends** at the moment we leave this site."*
O&G 1	*"The point is, if you remain **liable for something forever, then it will simply be removed**."*
Contractor 2	*"[Liability] would then have to be transferred to the government. that would be a precondition for leaving it. I don't think there is any ... I don't think there is anyone who wants to **have liability in perpetuity**."*
Govt 1	*"We **don't feel like taking [liability] over**. Because you are taking over something of which you have absolutely no idea what the extent is."*
Govt 2	*"The precondition is that it is **well marked in the nautical chart**, so that there is nothing to blame"*
Govt 2	*"I think that with offshore wind decommissioning, the monitoring and aftercare of it is **less exciting and less complex** [than for oil and gas], but keeping buoys and markings in place, for example, is still very important and also expensive."*

8. Policy recommendations

Based on the MCA results and subsequent discussion, recommendations for policy strategies are formulated. Efforts are made to take into account the three characteristics of the transition management theory (as described in 2.1.3): actor-networks, learning-by-doing, and long-term and adaptive management.

1. **Create a multi-stakeholder network well in advance of the actual decommissioning. Alignment and clarity across the playing field should be ensured in terms of concepts, objectives, regulations and priorities.**

At this point, discussions among stakeholders on offshore wind decommissioning do not seem to be present, likely because this phase is considered too far in the future. However, to ensure sustainability a long-term process and vision is required, instead of last-minute decisions. As the first offshore wind farms have to be decommissioned at the end of this decade, it is important to create a common understanding and awareness of the upcoming opportunities and challenges. Simultaneously, a multi-actor network makes it possible to oversee the stakes and considerations of each stakeholder, which makes it easier for authorities to weigh and prioritize interests (Schroeder & Love, 2004).

In order to determine the appropriate decommissioning strategy per wind farm, or even per monopile, it is critical to level the playing field in terms of what is considered environmentally beneficial. For example, "protecting the marine environment" is ambiguous, and dependent on whether it refers to enhancement of biodiversity, restoration of hard substrate, and/or exclusion of bottom-disturbing activities. Clarifying concepts such as *naturalness* and *value of nature* will provide better understanding of what the ultimate objective should be regarding North Sea nature and make the process of realizing it more manageable.

Moreover, since decommissioning requirements are poorly defined through legislations, the consequent assessment is also often vaguely executed (Gjødvad & Ibsen, 2016). Correspondingly, *Contractor 2* stated that “OWF contracts often include a decommissioning section” but is more a “check in the box”. Therefore, the government parties must provide regulatory clarity, so that the sector can be given clear guidelines and assurance for (sustainable) developments.

2. **Allow for a pilot site. This would allow opportunities and risks to be explored and tested in a safe and regulated manner, without setting a precedent by immediately relaxing regulations. Applying a "learning by doing" method can eradicate both financial and scientific uncertainties.**

There are still many uncertainties about how the environment will adapt to decommissioning strategies, as well as the costs involved. Therefore, a logical and urgent next step is to conduct extensive field research. The soonto-be decommissioned OWFs offer great opportunities to serve as test sites. Since PAWP is located close to shore and covers a relatively compact area, it offers opportunities for performing active monitoring while minimizing disturbance to other sea users.

An example of this pilot could be to dismantle the 60 monopiles of the PAWP in three different manners: 20 monopiles below seabed removal, 20 by only scour in situ, and 20 by Topping. Scientific research can then be carried out on short and long term effects of each strategy, such as contamination risks during decommissioning, species recovery rates, species abundance and degradation of materials. Furthermore, research can be conducted on how fishing is affected by leaving scour in place, but also vice versa: how does nature hold up if it does get bottom-trawled? Lastly, perhaps even unexpected opportunities for recreation can be found. Ultimately, all of this information gathered can lead to better science-based policy reforms of decommissioning regulations.

3. **Consider leaving scour in place after decommissioning, as long as some level of environmental protection can be maintained. Although some obstacles to implementing this alternative can be identified, such as lobbying from the fishing industry, it may provide an supported, profitable and sustainable strategy.**

This study shows that by leaving the erosion protection in situ and protecting the area from further disturbance, a widely accepted decommissioning strategy can be pursued where the costs and benefits are balanced. It is the only alternative that offers benefits for all criteria examined in this study. Both artificial reef effects on hard substrates and the return to some degree of naturalness through the removal of steel structures is ensured. However, a prerequisite for justifying the elimination of erosion protection is the establishment of a well-demarcated exclusion zone, because otherwise the environmental benefits are too uncertain and liability risks too high. Finally, removing steel brings recycling benefits, a revenue stream that could increase in value and importance over time, as OWFs get larger foundation structures and circularity targets are being strengthened.

When evaluated against the 10-tenet framework, this strategy appears to provide an integrated, sustainable and economically viable alternative (Table 24). Several pitfalls regarding implementing this strategy do exist, namely regarding its social desirability, culturally inclusiveness and legal boundaries. It is unclear whether leaving behind scour will receive sufficient political support, which depends on the extent to which activities of national importance can actually take place in the area without hindrance. Moreover, despite ranking high for almost all examined stakeholders, for the fishing industry this alternative is clearly disadvantageous. Clear communication with and close involvement of this stakeholder group can reduce opposition risks.

Table 24. Scour protection + MPA implementation alternative summarized for 10-tenets framework

10-tenets	**SPMPA**	Explanation (based on examples provided in Smyth et al., 2014)
Ecologically sustainable	High	Based on final combined-weight score of category 'environmental impact' compared to other alternatives: hard substrate increase, stone material is regarded somewhat natural, and protection to further habitat disturbance
Technologically feasible	High	Technologically feasible according to Contractors
Economically viable	High	Based on final combined-weight score of category 'economic profitability', yet actual costs remain somewhat uncertain
Socially desirable/tolerable	Medium	Widely supported by stakeholders, yet political expedience depends on whether activities of national importance may continue
Ethically defensible	Medium	No single sector is favored unduly, since this alternative remains beneficial in case of greenwashing investments
Culturally inclusive	Medium	Fisheries may be disadvantaged, which has impacts on decision-making due to their strong cultural image
Effectively communicable	High	Communication must be ensured through a framework for a coherent choice process, for which this study provides a basis
Legally permissible	Unclear	Remaining unclarity whether leaving scour in situ is legally permissible, difficult to adjust legislation both nationally and internationally when necessary
Administratively achievable	High	Based on existing governmental bodies, which exist for implementing MPAs, yet minimal experience in liability procedures currently
Politically expedient	Medium	Political support for scour in situ expected, yet MPAs are not activity of national importance and may experience implementation hinder

9. Conclusion

This study has responded to the demand for an interdisciplinary offshore wind decommissioning analysis with active stakeholder engagement by conducting a participatory multi-criteria analysis. Although previous studies did compare offshore foundation decommissioning strategies at 'high level' differences, this study examined several sub-options for partial removal as well, such as topping, only leaving scour in situ and a designated reefing area. Based on the *Triple Bottom Line* and *10-tenets* theoretical frameworks, seven alternatives were tested against a holistic criteria selection of economic, social and environmental dimensions. A wide variety of stakeholders, including operators, contractors, governmental representatives, fisheries, eNGOs and environmental experts, were involved in the establishment and implementation of the analysis, by providing both practical information as well indicating individual interests.

Decommissioning decision-making is often perceived as politically sensitive due to the involvement of various interests. Nevertheless, this study revealed that similar decommissioning alternatives may be preferred by stakeholders, even though the motivation for doing so is built on different reasoning. Especially MPA-alternatives appeared as beneficial strategies, which can be deduced from their costs effectiveness, high protection potential, and low residual liability costs compared to other alternatives. These three criteria were generally considered as highly important. Despite that MPA-alternatives might offer economically and environmentally desirable alternatives, their implementation is uncertain. They score relatively low on social acceptability, of which especially political compatibility, and ambiguity among stakeholders exists whether the established nature is *valuable enough* to protect.

Moreover, the assumptions about and the advantages of returning to pre-OWF habitat appear highly controversial. Leaving behind structures may be considered an opportunity to protect the area from soil-disturbing activities, recover hard substrate habitats and create connectivity between nature reserves. Nevertheless, also threats of leaving structures in situ were expressed, such as a precedent effect and artificial reefs of convenience. The resulting large-scale abandonment would be disproportionate. Therefore, prior to pursuing any conservation strategies, it is imperative to clarify exactly what is beneficial for the environment.

There is a need to ensure alignment and clarity across the playing field in terms of concepts, objectives, regulations, and priorities to facilitate the transition to widely supported and sustainable practices. In addition, a pilot site allows scientific uncertainties to be removed and therefore decisions to be better informed. Finally, viewpoints expressed from fisheries, in the context of their potential controversial place in the playing field, need to be better explored to ensure cultural inclusiveness.

Concluding, the upcoming kick-off of decommissioning in the Dutch North Sea at the end of this decade, offers a very rich opportunity to explore these complex but very interesting issues collaboratively. This study gives an indication of possible opportunities and has shown that bringing stakeholders together is crucial to get all parties on the same page. The sooner stakeholders are brought together to create a common understanding and share individual interests, the more economically, environmentally and socially sustainable solutions can be found.

Research limitations and recommendations

There are several limitations to this study. Firstly, only a limited number of criteria and representatives per stakeholder group were included in the MCA. Only one governmental organization provided MCA-weights, which indicates low representativeness. Moreover, there was a certain degree of arbitrariness in multiple scoring (e.g. recyclability rates of steel, whether leaving scour protection in situ will actually hamper fisheries and ocean accessibility). Also weighting by fisheries was based on assumptions, and although sensitivity analysis showed that this did not impact the framework as much, it does provide some uncertainty. Lastly, it must be acknowledged that stakeholders may have interpreted the criteria differently and thus their weights-feedback intentions may differ. For example, habitat alteration can be understood as the direct impacts of decommissioning, such as material resuspension, but also as the difference with the pre-OWF situation, i.e. introduction of artificial structures. Lastly, some of the criteria are interrelated (for example fisheries opportunity costs and protection potential), which may have impacted the final results.

Therefore, it is recommended that further research is carried out to address these issues and provide a more robust framework, for which this study can provide a basis. In order to decrease a potential bias in outcomes, an increased number of criteria and stakeholders should be included. Perhaps an interesting way to arrive at new insights would be to organize a stakeholder-debate rather than individual interviews. This could lead to practical or sensitive information brought to light that did not come up in a two-way conversation between researcher and interviewee. Regarding stakeholders, especially those higher up in the political system should be included to clarify the current North Sea objectives and regulatory enabling environment. In addition, efforts should be made to include fisheries in the weighting process. Moreover, efforts should be made to specify qualitative data in order to achieve clearer analysis results. Lastly, this analysis was conducted by using the PAWP windfarm as a case study. Although this is indeed one of the first OWFs to be decommissioned, at a later phase, this analysis should also be adapted to newer OWFs that are larger and further offshore. This might generate different results and conclusions.

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Appendix A. Analysis of previous used criteria

Table 25. Analysis of previous used criteria in O&G and Wind decommissioning decision-making literature

	Wind			Oil and gas		
	Kerkvliet (2015)	**Kerkvliet & Polatidis (2016)**	**Smyth et al. (2015)**	**Fowler et al. (2014)**	**Henrion et al. (2015)**	**Sommer et al. (2019)**
ECOLOGICAL (ecological sustainable)						
Increase in biodiversity / enhancement of diversity / species richness	X	X		X		X
(Increase in) biomass	X	X				X
(introduction & spread of) Invasive species	X	X	X	X		
Benthic impacts - Habitat damage from scattering debris - Smothering of soft bottom communities - Remobilized sediments	X	X	X	X	X	
Direct physical disturbance			X			X
Noise			X			
Water quality	X				X	
Emissions during decommissioning	X				X[14]	X[15]
Impact on marine mammals	X	X			X	
Impact on marine birds					X	
Energy use		X		X		X[16]
Gas emissions				X		
Contamination				X		X[17]
Production of exploitable biomass (spill-over effects)			X	X	X	
Conservation - Protection from trawling				X		X[18]
Provision of reef habitat				X		
Loss of developed community				X		
Facilitation of disease				X		
Alteration of trophic webs				X		
Alteration of hydrodynamic regimes				X		
Clear seabed				X		
Connectivity						X
ECONOMIC (economically viable)						
Cost of decommissioning	X	X	X		X	
Monitoring costs	X	X	X	X		
Maintenance costs	X	X	X	X		
Liability costs - Of property damage - Of personal injury	X		X	X		
Mobilization of support vessels				X		
Personnel				X		
Onshore processing				X		
Landfill				X		

[14] Air quality
[15] Energy consumption and carbon footprint
[16] Energy consumption and carbon footprint
[17] Dispersal
[18] Protection from trawling and spill-over effects

Replacement of construction materials				X		
Commercial fishing access - (indigenous fisheries)	X	X	X	X	X[19]	
Alternative commercial fishing activities			X			
Economic stimulus				X		
Shipping activity			X			
Health & Safety / Social (socially desirable/tolerable)						
Navigation (hazards)	X			X		
Fishing hazards				X		
Project risk to personnel offshore - Crushing accidents				X		
Project risk to other users of the sea / residual risk			X			
Exposure to drilling mud				X		
Exposure to toxic construction materials				X		
Public access	X	X	X	X	X[20]	
Public sentiment				X		
Risks	X					
Employment creation/opportunities	X			X		
Taxation concessions				X		
Diving opportunities			X	X		
Cultural impingements				X		
Unobstructed ocean view				X		
Recreational fishing opportunities	X		X	X		
TECHNOLOGICAL (technological feasible)						
Track record	X					
Practical knowledge			X			
POLITICAL (legally permissible + administratively achievable)						
Currently accepted by law			X			
Politically expedient			X			

[19] Ocean access
[20] Ocean access

Appendix B. Detailed background criteria scoring

Decommissioning costs

To the author's knowledge, no exact figures and very few estimates of monopile and scour decommissioning costs exist. Estimates are available for the entire OWF decommissioning process. Topham & McMillan (2017) mention an estimate £200,000-600,000/MW; Kaiser & Snyder (2012) estimate $115,000-135,000/MW, and TNO (2020) mentions estimated costs of €1.6M for a 2 MW turbine. Foundation decommissioning are expected to account for approximately 45% of total costs (Topham & McMillan, 2017; TNO, 2020). Complete removal is expected to be 30% more costly than partial removal (Jadali et al, 2021), yet costs differences at the level of alternative variations examined in this study has not been conducted. For this reason, deriving costs based on these estimations remains highly uncertain. Additionally, costs will change significantly over time, as decommissioning costs are likely to decrease with experience. Therefore, to assess this criteria, a qualitative score was provided based on literature and input from stakeholders. Weight of the monopile is expected to be the most impactful parameter (Topham & McMillan, 2017; Adepipe & Schafiee, 2021). For example, in case of reefing structures elsewhere, these first have to be lifted and subsequently relocated, this will greatly increase installation and deinstallation time, and consequently costs (*Contractor 3* and *4*).

- Complete monopile removal poses major costs due to heavy weights and complex engineering procedures (Fowler et al., 2018; Kaiser & Snyder, 2010). Additionally, heavy-weight vessels for lifting the structures are needed, which may differ from the transportation vessel (Kaiser & Snyder, 2010). Due to these time-consuming and equipment intensive activities, full decommissioning is expected to be least economically viable (Topham & McMillan, 2017). Lastly, as full removal techniques are still in development and are thus accompanied by a certain degree in newness and uncertainty, this strategy is expected to bring high costs in the near future (*Contractor 3*).
- *Operators* and *Contractors* agree that leaving structures in place is always cheaper in terms of decommissioning costs. Accordingly, Topping is expected to be the most cost-effective method, followed by only scour left in place (*Contractor 3*).
- Regarding DRA, costs depend on the distance between decommissioned site and appointed reefing area. When structures first have to be lifted and subsequently relocated, this will greatly increase installation and deinstallation time, and consequently the costs (*Contractor 3* and *4*). Since a monopile first has to be partially removed, followed by grabbing the scour and relocating both, it is expected to be at least as costly as full removal.

Opportunity costs: trawl-fisheries

Until 2020 windfarms OWEZ, PAWP, Luchterduinen and Gemini occupied 133 km^2, approximately 0.23% of the NCP. This increases to 1600 km^2 (2.8%) by 2030, which mainly affects fisheries in the southern part of the Dutch

North Sea where bottom-trawling on sole-fishing is dominant[21]. This area contributes approximately €1.52 million per year to the gross value added, during the period 2010-2017. This is approximately 2.65% of the total gross value of bottom-trawling fisheries on the Dutch North Sea. Bluntly calculated, €950 per km2 is lost, thus a loss of €13.300 yearly for the 14 km^2 PAWP site. Two assumptions were made: fisheries are not hindered by scour protection, and in an MPA no trawl-fishing is allowed. In the case of topping without MPA implementation, it is taken into account that the fishery will avoid physical interference with the 'topped monopile' by obeying a safety zone with a 50 meter radius[22]. However, fisheries experience additional inconvenience due to avoiding these structures, therefore increasing operational costs (*Fisheries 1*).

- For Topping, the safety-zone in an OWF (distance of 50 meters[23] from these structures) is expected to be maintained. Therefore, the 60 wind turbines present will result in an avoided area of approximately 0.468 km^2 (7800 m^2 per monopile). This results in €444,60 opportunity costs. However, *Fisheries 1* states that a loss does not only depend on the size of the area, but also on practical aspects. Since fishing practices will be complicated due to avoiding these structures, costs will inevitably be higher than this (Table 26). For this reason, at least double the opportunity costs is assumed: €1000.
- According to *Govt 2*, with current scour-rock dimensions there exists no obstacle to the fishery using trawls. In the event that the scour is abandoned and the monopiles are cut below the seabed, yet without implementing an MPA, fishing can resume. Hence the yield of the entire area will be taken into account again and opportunity costs are absent.
- If an MPA is established, it will remain an exclusion zone of 14 km^2 where trawl fisheries are prohibited, therefore having similar opportunity costs as during the operational phase of the OWF: €13.300. This accounts to both MPA alternatives (TMPA and SPMPA).
- When implementing a DRA, the opportunity costs will be €950 since only 1km2 has to be avoided.

Table 26. Statement of stakeholder on Fisheries

Stakeholder	Statement
Fisheries 1	*"The shortage of space, that's one thing. But for fishing you do not only need a lot of space, you need to* ***be able to sail in a straight line*** *for two hours. "*

Monopile recycling revenue

This criteria focuses on the steel recycling since this is deemed most certain and profitable in the future (Gokhale, 2020). Although several ideas exist on the recycling of scour protection and the attached 'marine growth' (Fortune & Paterson, 2020), this is still very hypothetical. Steel generates a high recycling value because it is used in large quantities and due to its recyclability (Gokhale, 2020). The exact revenue is dependent on the scrap market value, which TNO (2020) recently estimated at €100-300 per ton steel and uses a recycling rate of 95%,

[21] The impact of offshore wind on fisheries, at https://windopzee.nl/onderwerpen-0/effect-op/activiteiten/visserij
[22] Policy for establishing safety zone for offshore wind farms, at https://wetten.overheid.nl/BWBR0042533/2018-05-01
[23] Policy for establishing safety zone for offshore wind farms, at https://wetten.overheid.nl/BWBR0042533/2018-05-01

which is taken into account in these calculations as well. A scrap market value of €300 per ton steel is used and it is assumed that no bio-coating or other chemicals on the monopiles hinder the recycling process.

As PAWP consists of 54 meters long monopiles being 320 tons of steel each (Vanagt & Faasse, 2014). This means that if no steel is lost during recycling, €96000 can be earned. Logically, complete removal of a monopile provides the most steel for recycling, followed by cutting the monopile 4.5 meters below the seabed (includes BS, SP and SPMPA), and topping the monopile by cutting 2 meters above the seabed. In case of a DRA, no steel is brought ashore to be recycled. However, uncertainty exists in both scrap market value and recycling rate developments (*Operator 1*). Additionally, stakeholders express different views on the potential of recycling (Table 27).

Table 27. Statements of stakeholders on Steel recycling

Stakeholder	Statement
Contractor 4	*"I think the **cost of removal is many times higher** than what you get back from recycling."*
Operator 2	*"At the moment, for example, the **recycling of materials is not highly valued**, so to speak."*
Consultant 1	*"That steel can also be reused. So in that sense, you could say that it is **good to take it out** completely."*

Residual liability costs

Concrete data on liability costs seems unavailable. Moreover, monitoring and maintenance costs are greatly difficult to estimate, since these depend on the type of material left in place and unpredictable risks (Adepipe & Schafiee, 2021). Therefore, to assess this criteria, a qualitative assessment was carried out based on the available literature and input from stakeholders, mainly from *Govt* and *Operators*. The higher the risk of environmental or safety hazards, the higher the score.

Worth mentioning is the expected difference in liability costs when only leaving scour behind versus also leaving some monopile structure above the seabed. While the former will most likely include only uncomplicated monitoring and maintenance, the latter includes inspections for possible discharges of hazardous and polluting substances, along with a potential safety risk to vessels (*Govt 2*). Contrary, it is assumed that when an MPA is implemented, residual liability becomes analogous to that of exclusion zones that existed during the OWFs operational phase. This means that the liability for any accidents lies with the border-crossing party (*Govt 2*). However, and this is paramount, it must be properly marked on the nautical charts (*Govt 2*).

- In case of full removal or partial removal below seabed, no residual liability costs exist since the seabed is cleared.
- As aforementioned, current scour protection dimensions are not expected to impose any safety risks. Nonetheless, whilst scour protection is not expected to be a substantial source of liability costs as it is composed of natural materials, it does need to be looked after to check whether it remains in place (*Govt 2*).

- Monopile parts left in situ should be inspected yearly for possible discharge of hazardous and polluting substances (*Govt* 2). Topped monopiles also pose a threat to any vessel that comes into contact with the remaining structure, especially bottom-trawling fisheries (*Consultant 2, Govt 3*).
- It is assumed that when an MPA is implemented, the liability becomes analogous to that of exclusion zones that already existed (*Govt 2*). In case a prohibited vessel ventures into the site, it becomes fully responsible for any accidents caused by collisions with the structures. Hence, the residual liability costs in the MPA alternatives are lower than when this is not the case, similar to a DRA. However, and this is paramount, it must be properly marked on the nautical charts. Furthermore, it is assumed that that the government becomes responsible for any potential environmental risks as they take over the MPA management in this case.

Biodiversity

There seems to be scientific consensus that complete removal and below seabed removal will negatively affect local biodiversity due to the loss of hard substrates (Adepipe & Schafiee, 2021; Fortune & Paterson, 2020; Sommer et al., 2019). Apart from potential but uncertain differences in temporary effects during decommissioning (e.g. noise), full removal and partial removal under the seabed are not likely to significantly differ in terms of biodiversity. The pre-OWF habitat, namely soft sediment communities, typically exhibit lower diversity than the operational phase (Fortune & Paterson, 2020; Teunis et al., 2021). Moreover, when fully removing a monopile, species could face mortality due to potential shock waves (Fortune & Paterson, 2020) or be driven away due to sound impacts (*eNGO 3*).

According to *Ecologist 1*, leaving the structures in place is expected to be most ecologically beneficial. Partial removal allows species to be retained that were absent prior to OWF installation by leaving some degree of hard substrate in situ (*Ecologist 1*). It also allows the opportunity for species to settle inside the topped monopile, thereby being protected from currents (*Ecologist 1*).

In the long run a DRA is expected to show highest local biodiversity levels due to increased habitat complexity, with habitat in all possible orientations (*Ecologist 1*). However, relocation activities do require impactful scraping, lifting and subsequent dumping activities, due to which attached organisms may not survive (*Ecologist 1*). Moreover, moving the components somewhere else may introduce invasive species in these designated places, which may threaten the biodiversity (Fortune & Paterson, 2020).

Leaving scour in place can lead to higher biodiversity compared to pre-OWF situations due to the presence of hard substrates. However, continued survival will depend on several factors: whether the scour will be buried eventually, and whether bottom-trawling fisheries will actually be hindered by the present scour. This could nullify the hard substrate effect on the seabed (*Ecologist 1*). In this assessment, we assume that fishing can proceed when scour is left in place, and scour will not be buried in the long-run.

Natural habitat alteration

Habitat alteration is an ambiguous concept, the interpretation of which depends entirely on the situation to which it relates. On the one hand, during the actual decommissioning activities, as little impact to the benthic habitat as possible is desirable to preserve nature (Birchenough & Degraer, 2020). This closely relates to the biodiversity criteria discussed above. On the other hand, as is strongly emphasized by eNGOs, the *original* state of the environment pre-OWF is also a highly important environmental factor that should be taken into account (*eNGO 2* and *3*). From this perspective, leaving structures in situ is regarded as marine littering, thereby altering the environment towards unnatural habitats. For this criteria, alternatives are scored based on this perspective of recovery of 'naturalness'

During interviews, it became evident that leaving scour behind is considered less unnatural than leaving steel behind (*Consultant 1 and 2, Operator 2, Govt 1 and 3*). Therefore, alternative SP would be more beneficial than T, scoring somewhat altered (+) and substantially altered (++) respectively. The MPA alternatives are similar to their non-MPA related alternatives. Implementing an DRA, thus leaving all structures behind, is scored as substantially altered (++). With CR all structures are removed (+-).Remaining sub-seabed structures are not taken into account in this assessment, therefore BS also scores +- since the seabed is cleared.

Protection potential

Protection potential depends on the size of the OWF and the density of the plot in terms of wind turbines. PAWP has 60 monopiles that are spaced 550 meters apart (Leopold et al., 2013) over an area of 14 square kilometers, each surrounded by a 15 m diameter scour protection (Vanagt & Faasse, 2014).

- Logically, in alternatives TMPA and SPMPA, their status as MPA considers them as exclusion zones for commercial shipping and fisheries, therefore having full protection potential (14 km^2 protected).
- Contrastingly, alternatives CR and SB will result in pre-OWF situations, where all heavy vessel and bottom-trawling fisheries may enter again (0 km2 protected).
- T and DRA are expected to result in a certain loss of area where bottom-trawling fisheries and large vessels cannot safely operate. In this case, the surface area of the monopile and included safety zone (0.468 km2 in total for 60 turbines) is avoided. However, similar to lost fishing ground as aforementioned, when including convenience considerations, it is assumed this area covers $1km^2$. In case of a DRA, also $1km^2$ is avoided.

Ocean access

When a party can fully access the site, a score of 1 is given, for somewhat accessible 0,5, and 0 for inaccessible. When structures are left behind, below or on top of the seabed, this is assumed to physically hinder further seafloor-based activities, such as sand, oil or gas extraction (in case of BS, T, SP and DRA). Although oil and gas activities are expected to be hindered from MPAs, according to *Govt 2,* sand replenishment is not expected to be completely banned from designated nature areas. This could be due to its importance for coastal strengthening and hence national safety. In case of Topping, also shipping and military exercises are hindered due to navigational safety issues. It is important to note that these are assumptions and may vary depending on the situation under real circumstances.

Table 28. Expected accessibility of activities of national importance after decommissioning

	CR	BS	T	TMPA	SP	SPMPA	DRA
Shipping	1	1	0.5	0.5	1	0.5	1
Sand extraction	1	0.5	0.5	0.5	0.5	0.5	0.5
O&G	1	0.5	0.5	0	0.5	0	0.5
Wind energy	1	0.5	0.5	0	0.5	0	0.5
CO2-storage	1	0.5	0.5	0	0.5	0	0.5
Military exercises	1	1	0.5	0	1	0	1
%	**100**	**67**	**50**	**17**	**67**	**17**	**67**

Recreational opportunities

In alternatives where an MPA is implemented (TMPA and SPMPA), recreation gets a chance to thrive as no industrial activities interfere with sailing, fishing or diving activities (++). *Recreation 1* argued that the 12-mile zone is the most heavily used sailing area, and as PAWP lies on the outer edge of this 12-mile zone and it is assumed to be attractive as well. Without an MPA, recreational activities seem less likely due to navigational risks and safety issues that could arise. Only as far as Topping is concerned, recreational fishing can be increased as a result of large industrial vessels avoiding the monopiles (+), while leaving scour in place is expected to have no effects (+-). A DRA can be attractive for both sport fishing and diving, because of the greater biodiversity gathered in one area, and an exclusion zone for industrial activities, yet due to the small area is not expected to have a positive effect on sailing (++). CR and BS are expected to show no differences in recreational activities, since the post-decommissioning situation will be similar to the pre-OWF situation (+-).

Table 29. Stakeholder statements on Recreational opportunities

Stakeholder	Statement
Consultant 2	*"I think [recreational opportunities] are especially relevant for locations **close to the coast**."*
Ecologist 1	*"[There could be recreation] but a very small chance, because there are **not that many divers.** […]. **Sport fishing is a big opportunity**, of course."*
Govt 3	*"[Recreational opportunities] would probably not go **beyond rod fishing indeed, or diving**."*
Contractor 4	*"This is offshore, several kilometers out of shore. I see **limited possibility for any recreational activities** in this harsh region compared to nearshore region."*

Political compatibility

Despite that several other criteria are also somewhat arbitrary due to their hypothetical nature and lack of hard data, 'political compatibility' is the most challenging to score. This is because it depends on which public authority is being questioned, which interests are being balanced and what national and regional objectives are prioritized. Nevertheless, this criteria is considered highly valuable by all stakeholders interviewed, as it demonstrates the suitability of the enabling policy environment, adding that it also includes a degree of social acceptability. Additionally, Schroeder & Love (2004) state that in case of high scientific uncertainty, which applies in this study, political values, among others, gain importance in the decision-making process. Therefore, this criteria is deemed crucial in this framework.

To estimate the political support, government parties were interviewed, from which three guiding statements were eventually drawn. These were compared to the alternatives, for which scores ranged from high (1 point), medium (0.5), to low (0) (Table 30). The statements are:

- At present, policymakers will never focus exclusively on nature protection in spatial planning of the North Sea, because of the high value of other economic and infrastructural activities and because the value of nature is not (yet) sufficiently high (*Govt 2)*. Simply put, the government does currently not want to 'sacrifice' complete areas to nature. Nature conservation and enhancement measures are therefore expected to be adopted only in conjunction with other activities. Consequently, there is limited support for the designation of an exclusive ecological zone (*Govt 2*).
- When for well-founded ecological, economic and/or social reasons, structures are abandoned, greater support is expected for leaving only scour material behind, rather than steel (*Govt 3*). Therefore, alternatives leaving steel behind receive lower scores.
- In case there are any safety risks for other sea users, a strategy is very likely to show low support (*Consultant 2*). Hence, this has a major impact on the abandonment of objects and the designation of exclusion zones. Consequently, leaving structures behind without MPA implementation (in which the exclusion zone reduces safety risks) receive lower scores.

Table 30. Scoring of alternatives on expected political support

	CR	BS	T	TMPA	SP	SPMPA	DRA
Multi-use	1	1	0,5	0	1	0	1
Clearance	1	1	0	0	0,5	0,5	0,5
Safety	1	1	0	1	1	1	1
Total score	**3**	**3**	**0,5**	**1**	**2,5**	**1,5**	**2,5**

Appendix C. Sensitivity analysis

Fisheries

Figure 14 shows the results of removing the Fisheries weights from the framework and calculating the scores, combined with the original outputs. Ranking remains the same, yet total scores are lower. Especially DRA, which makes the biggest drop. This is due to that the arbitrary weights of fisheries where relatively high (e.g. 45 points to opportunity costs of trawl-fisheries), while the weights of other stakeholders are more 'spread out' over the criteria. Thus, despite the fact that fishing has the lowest impact on mean weights, these "extreme points" do result in higher scores for some criteria. However, since this occurs to some degree in all alternatives, this is not considered a problem. Also ranking is highly similar in both scenarios. TMPA remains highest in rank, followed by SPMPA. Without Fisheries weights, CR and BS become equally weighted, as do T and DRA. The rest of the ranking remains the same.

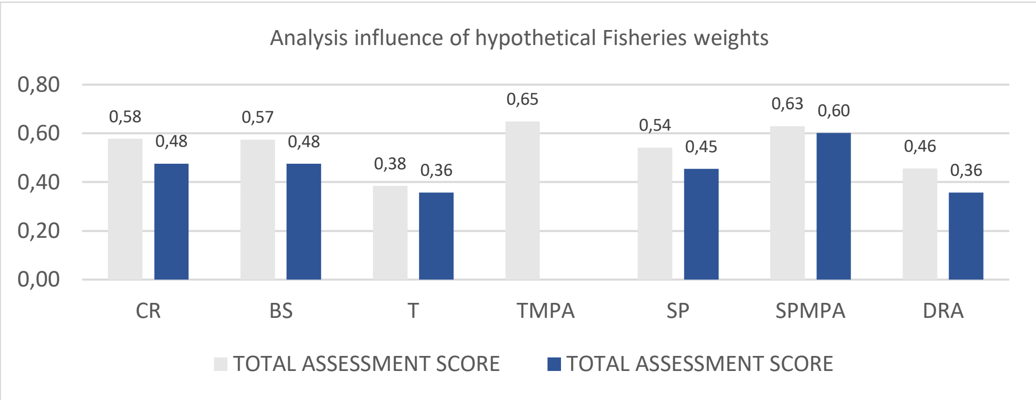

Figure 14. Sensitivity analysis for including or excluding hypothetical Fisheries weights

Cost-effective complete removal and designated reefing area

Scenario-analyses explained in main text

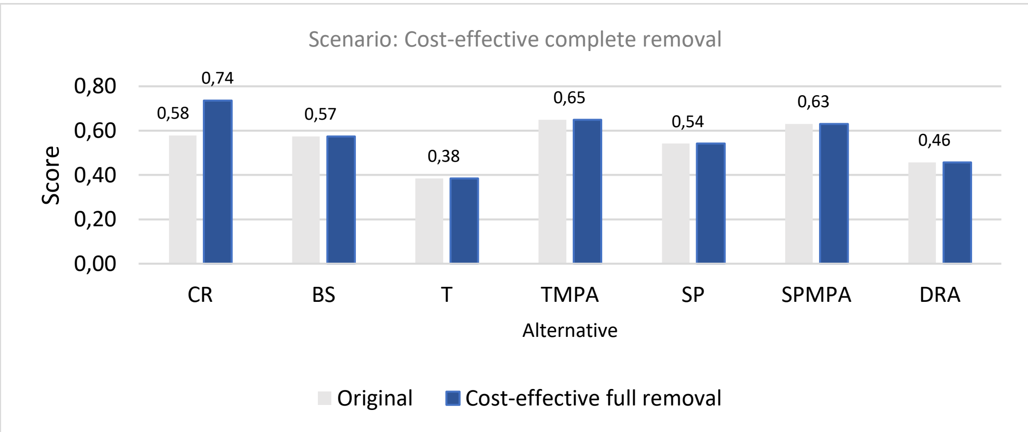

Figure 15. Scenario-analysis of cost-effective complete removal (decommissioning costs significantly lower --)

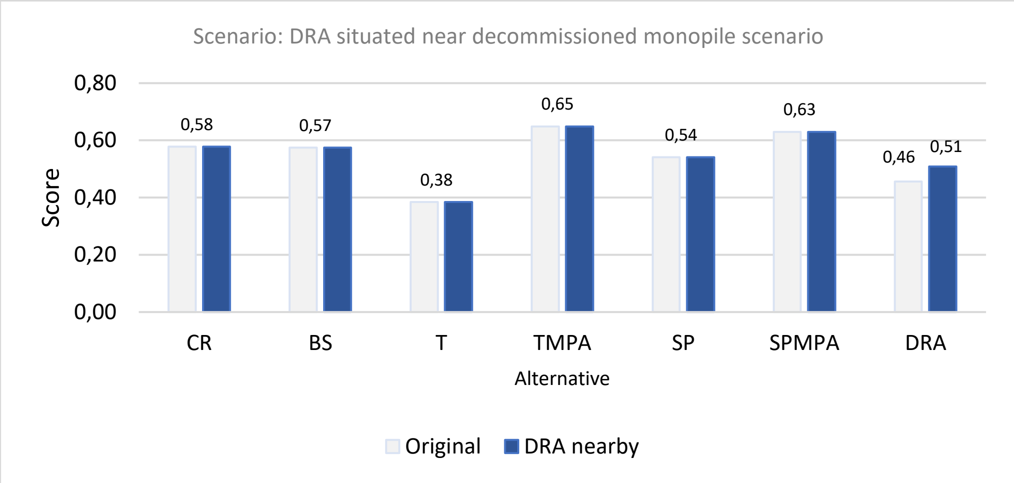

Figure 16. Analysis of situation in which DRA is nearby decommissioned monopile (decommissioning costs significantly lower --)

General weighting analysis

Also more general weighting sensitivity-analyses were conducted: standard weighting, extreme weighting for social criteria, and extreme weighting for environmental criteria. The methods are explained in Table 31. The results are summarized in Figure 17. Moreover, Figure 18 provides more detailed information on how the scores are constructed from the three categories of criteria.

Although the composition of the criteria that make up for a particular score differ among the scenarios, the ranking remains quite similar in all three cases when compared to the original MCA results. Some outliers are SPMPA, in which extreme environmental weighting boost this alternative upwards, and Topping, in which both extreme weights lead to lower scores. The scores per category that make up these final scores do differ from one another, yet overall, the final scores seem quite robust to weight-changes. Not surprisingly, in extreme weights, the category that these weights are applied to, score higher than in their original MCA counterpart.

Table 31. General sensitivity analysis scenarios

Analysis	Description
Standard weighting	Sensitivity analysis in which all weights of all three categories (economic profitability, environmental impact and social acceptability) are equally divided: 33,33 points out of 100 per category.
Extreme weighting: social acceptability	Sensitivity analysis in which weights of category economic profitability are halved, and weights of social acceptability are doubled.
Extreme weighting: environmental impact	Sensitivity analysis in which weights of category economic profitability are halved, and weights of environmental impact are doubled.

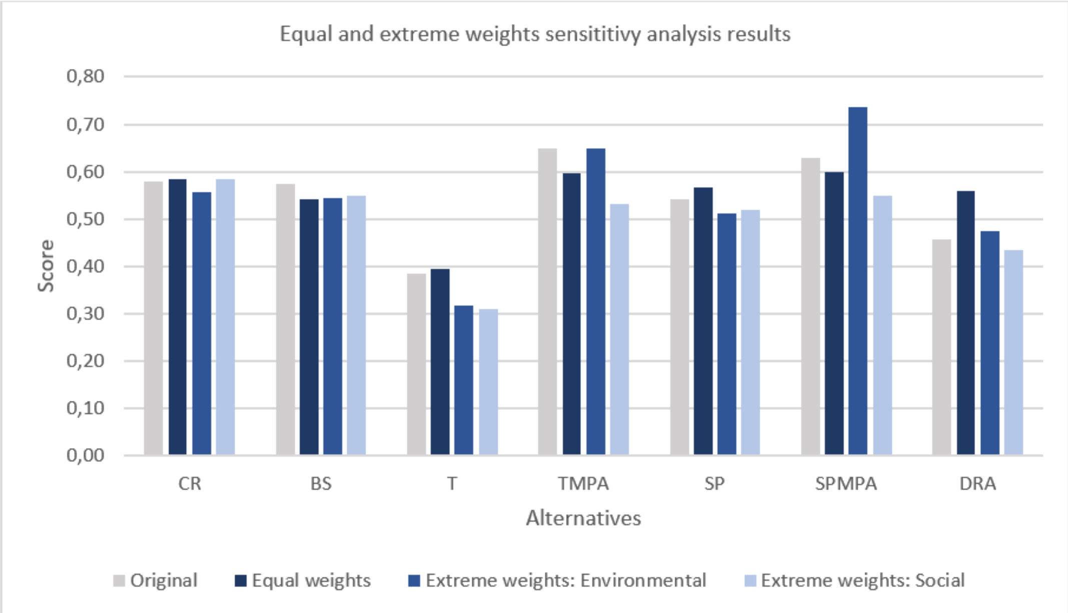

Figure 17. Summary of results of equal and extreme weighting sensitivity-analysis

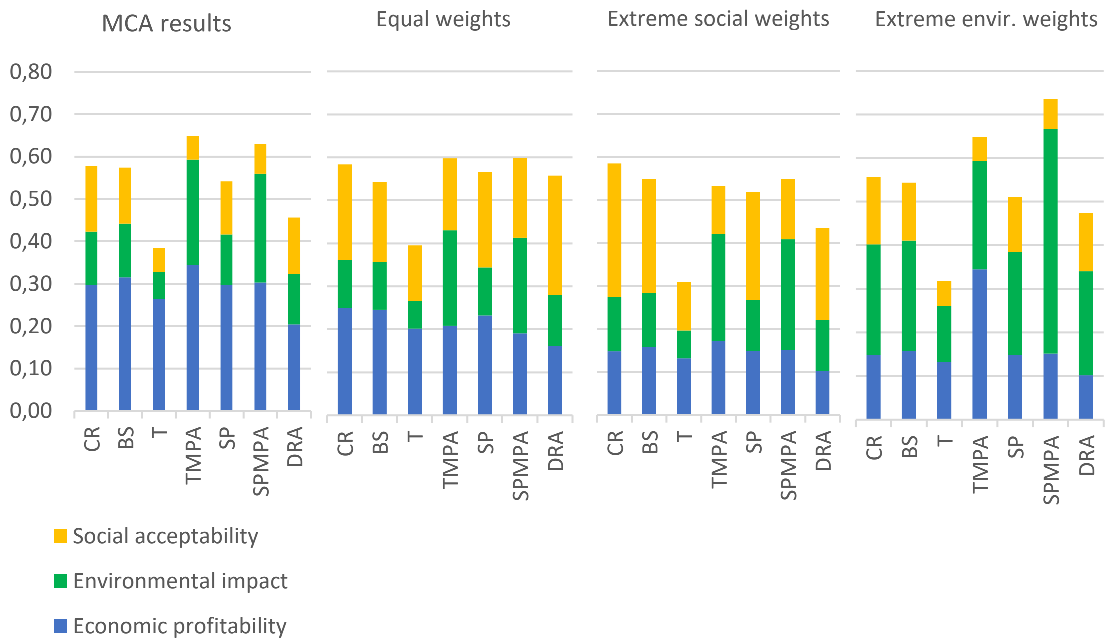

Figure 18. Results of MCA-results and of individual weighting sensitivity-analyses