Sustainable offshore wind farm decommissioning

Multi-criteria decision analysis for the assessment of sustainable decommissioning alternatives

Dissertation

By Vanessa Spielmann

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SeeOff Strategieentwicklung zum effizienten Rückbau von Offshore-Windparks

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Dedicated to my children

Mara Ayla, born 20.06.2020

Moe Nuri, born 05.09.2022

Summary

The current ambitious plans for the development of wind generated electricity call for the construction of a large number of offshore wind turbines in the North Sea. As the operational lifetime of each of these wind turbines is finite, decommissioning of offshore wind farms (OWF) becomes a core question of sustainable energy management. However, currently we lack both practical experience in decommissioning as well as a thorough understanding of opportunities and limitations of different decommissioning alternatives. Possible decommissioning alternatives consider, for example, partial or complete decommissioning, different dismantling technologies or logistical concepts. Economic, environmental and social impacts of these decommissioning alternatives are not completely examined. So, due to very few experiences and knowledge, the decommissioning of OWFs is associated with a lot of uncertainty. This thesis aims to enable decision-makers to make qualified and comprehensible decisions on sustainable OWF decommissioning. Multi-criteria decision analysis (MCDA) was applied to assess and compare selected decommissioning alternatives with regards to their sustainability, i.e., their greenhouse gas (GHG) emissions, resource efficiency, costs, hazards and impact on benthic biodiversity, while accounting for the associated uncertainty.

Due to the lack of experiences, first of all, a knowledge base was established on which all consecutive analyses were based on. This knowledge base includes a stakeholder analysis (publication I), the development of decommissioning alternatives (publications V and VIII), the investigation of the legal basis (publication II) and the description of a reference OWF (publication III). Thereafter, a framework was developed, that integrates stakeholder, sustainability and processes approaches (publication IV). It serves as a basis for the MCDA. Different MCDA methods (the weighted sum model (WSM) in publication VIII and fuzzy SAW, fuzzy TOPSIS and fuzzy VIKOR in publication IX) were applied and the results were interpreted focusing on the comparison of the MCDA methods and the decommissioning alternatives. In order to investigate the impacts of the weighting of the decision criteria on the ranking of the decommissioning alternatives an assessment with overweighted criteria was conducted (publication X).

This study demonstrates, how MCDA can be applied to assess the sustainability of alternatives of OWF decommissioning. While all four MCDA methods proved to be suitable, the three fuzzy MCDA also account for uncertainties associated with the decommissioning project. Even though, the methods responded differently to small deviations in the fuzzy ratings under certain circumstances, they mostly produced similar ranking of the decommissioning alternatives. Partial decommissioning alternatives were mostly ranked highest, i.e., alternatives where foundation structures are cut above seabed, scour protection and/or inter-array cables are left in situ. They are associated with low *costs*, *GHG emissions* and are beneficial for the benthic *biodiversity*. Contrary, the feeder concepts were ranked lowest most often. They are associated with higher *costs*, *GHG emissions* and *hazards*, as they involve additional vessel and transits as well as more lifts.

Sustainability, i.e., the pursuit of environmental, economic and social objectives, was accounted for by considering five decision criteria in the MCDA. Four of them, i.e., *costs*, *GHG emissions*, *biodiversity* and *hazards* have proven to be suitable criteria to assess the alternatives of OWF decommissioning considered in this analysis. The decision criterion *resource efficiency*, however, was not suitable to assess partial decommissioning alternatives as it did not appropriately account for the amount and types of materials that remain at sea.

A fundamental challenge of this analysis was the weak data and knowledge basis. Due to the lack of experiences, decommissioning processes were developed based on the opinion of experts. Data for the assessment of the decommissioning alternatives was also limited, either due to confidentiality, such as vessel fuel consumptions, or non-exitance, e.g., as for environmental monitoring data. In order to improve analysis on OWF decommissioning, further research should focus on acquiring such data and information.

Zusammenfassung

Die aktuellen ehrgeizigen Entwicklungspläne für Windenergie erfordern die Errichtung sehr vieler Windturbinen in der Nordsee. Da die operative Lebensdauer dieser Windturbinen endlich ist, wird der Rückbau eine der Kernfragen des nachhaltigen Energiemanagements. Zurzeit mangelt es jedoch sowohl an praktischen Rückbauerfahrungen als auch an einem fundierten Verständnis für Chancen und Limitationen der unterschiedlichen Rückbaualternativen. Mögliche Rückbaualternativen berücksichtigen zum Beispiel verschiedene Rückbautechnologien, logistische Konzepte oder teilweisen Rückbau. Ökonomische, Umweltbezogene oder soziale Auswirkungen dieser Rückbaualternativen sind bisher nicht vollständig untersucht. Aufgrund der sehr geringen Erfahrungen und Kenntnissen ist der Rückbau von Offshore-Windparks mit einer großen Unsicherheit verbunden. Diese Arbeit hat zum Ziel, Entscheidungsträger zu befähigen qualifizierte und nachvollziehbare Entscheidungen für einen nachhaltigen Rückbau von Offshore-Windparks zu treffen. Multikritierelle Entscheidungsanalysen wurden angewandt um ausgewählte Rückbaualternativen hinsichtlich ihrer Nachhaltigkeit, d.h. ihrer Treibhausgasemissionen, Ressourceneffizienz, Kosten, Gefährdungen und Auswirkungen auf die benthische Biodiversität, unter Berücksichtigung der einhergehenden Unsicherheiten zu bewerten und zu vergleichen.

Aufgrund der mangelnden Erfahrungen wurde als erstes eine Wissensbasis entwickelt, auf welcher alle nachfolgenden Untersuchungen basierten. Diese Wissensbasis umfasst eine Stakeholder-Analyse (Publikation I), die Ausarbeitung der Rückbaualternativen (Publikationen V and VIII), die Untersuchen der rechtlichen Anforderungen (Publikation II) und Entwicklung eines Referenz-Offshore-Windparks als Fallbeispiel (Publikation III). Anschließend wurde ein Konzept entworfen für die Integration von Stakeholder-, Nachhaltigkeits- und Prozessansatz (Publikation IV), welches als Basis für die multikriterielle Entscheidungsanalyse diente. Unterschiedliche Methoden der multikritierellen Entscheidungsanalysen wurden angewendet (Nutzwertanalyse in Publikation VIII und fuzzy SAW, fuzzy TOPSIS sowie fuzzy VIKOR in Publikation IX) und die Ergebnisse wurden zwecks des Vergleichs der Methoden und der Rückbaualternativen interpretiert. Um die Auswirkungen der Gewichtung der Entscheidungskriterien auf die Rangfolge der Rückbaualternativen zu untersuchen wurde eine Auswertung mit übergewichteten Kriterien durchgeführt (Publikation X).

Diese Studie zeigt, wie multikriterielle Entscheidungsanalysen eingesetzt werden können, um die Nachhaltigkeit von Rückbaualternativen von Offshore-Windparks zu untersuchen. Obwohl alle einsetzten Methoden geeignet waren, berücksichtigten nur die fuzzy Multikriterielle Entscheidungsanalsysemethoden die assoziierte Unsicherheit. Obwohl die Methoden unter bestimmten Bedingungen unterschiedliche auf kleine Abweichungen in den fuzzy rating reagierten,

haben sie größtenteils ähnliche Rangfolgen der Rückbaualternativen hervorgebracht. Alternativen des teilweisen Rückbaus, bei denen Gründungsstrukturen oberhalb des Meeresbodens geschnitten werden, der Kolkschutz und/oder die Innerparkverkabelung zurückbleibt, erhielten zumeist hohe Range. Sie sind mit geringen Kosten und Treibhausgasemissionen verbunden und sind vorteilhaft für die benthische Biodiversität. Feeder-Konzepte wiederum gehen mit hohen Kosten, Treibhausgasemissionen und Gefährdungen einher, da sie zusätzliche Schiffe und Überfahrten sowie mehrere Hebevorgänge erfordern. Sie erhielten somit am häufigsten die niedrigsten Ränge.

Nachhaltigkeit, also die Verfolgung umweltbezogener, wirtschaftlicher und sozialer Ziele, wurde durch die fünf Entscheidungskriterien in der multikriteriellen Entscheidungsanalyse berücksichtigt. Diese Analyse zeigt, dass vier der Entscheidungskriterien, nämlich Kosten, Treibhausgasemissionen, Biodiversität und Gefährdungen, geeignete Kriterien sind, um die Rückbaualternativen für Offshore-Windparks zu bewerten. Das Entscheidungskriterium Ressourceneffizient jedoch ist nicht geeignet, um teilweise Rückbaualternativen einzuschätzen, da die Menge und die Art der im Meer verbleibenden Materialien nicht angemessen berücksichtigt werden.

Eine grundlegende Herausforderung dieser Analyse war die schwache Daten- und Wissensbasis. Aufgrund mangelnder Erfahrungen wurden Rückbauprozesse basierend auf der Einschätzung von Experten entwickelt. Daten für die Bewertung der Rückbaualternativen unterlagen häufig der Geheimhaltung, z.B. der Treibstoffverbrauch der Schiffe, oder sie existierten nicht, so wie z.B. Umweltmonitoring-Daten. Um den Rückbau von Offshore-Windparks besser untersuchen zu können, sollten künftig solche Daten und Informationen erhoben werden.

Abbreviations and acronyms

AWJ	Abrasive water jetting
BISAR	Biodiversity Information System of benthic species at ARtificial structures (BISAR)
CER	Cause-effect relationship
EEZ0	Exclusive Economic Zone
FOU	Foundation structure
GAMM	Generalised additive mixed model
GBS	Gravity based structures
GHG	Greenhouse gas
HSE	Health, Safety, Environment
IAC	Inter-array cable
JUV	Jack-up vessel
LCA	Life-cycle assessment
MCDA	Multi-criteria decision analysis
MP	Monopile
OSS	Offshore substation
OWF	Offshore wind farm
ProCr	Criteria for the selection and exclusion of processes
ProOpt	Decommissioning Process Option
SAW	Simple additive weighting
SDG	Sustainable Development Goals
SPL	Scour protection layer
SPMT	Self-propelled modular transporter
StakeCat	Stakeholder category
StakeGr	Stakeholder group
SustAsp	Sustainability Aspect
SustAttr	Sustainability attribute
SustCat	Sustainability category
SustDeCr	Sustainability decision criteria
SustObj	Sustainability objective
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TP	Transition piece
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje
WSM	Weighted sum model
WTG	Wind turbine generator

Content

CHAPTER 1

INTRODUCTION

1 Introduction

Sustainable and renewable energy production is a topic of international interest, as set out in the 7th Sustainable Development Goal (SDG) 'Ensure access to affordable, reliable, sustainable and modern energy for all' in 'Transforming our world: the 2030 Agenda for Sustainable Development' by the United Nations. Offshore wind energy, as a renewable energy source, should be sustainable over the entire life-cycle - including its end-of-life. Considering the three pillars of sustainability (economic, environment and social) when decommissioning offshore installations has not always been (and not always is) the case. A well-known example is the decommissioning of the oil platform *Brent Spar* by Shell UK in the 1990th. Initially, the company intended to sink the platform. However, after a public indignation, initiated by a Greenpeace campaign and occupation of the platform, Shell UK was forced to refrain from their plans. Currently, decommissioning programmes for the platforms *Brent alpha*, *Brent Bravo* and *Brent Charlie* are being developed, addressing safety-related and environmental impacts and economic aspects (Shell UK, n.d.). Therefore, large-scale decommissioning project can draw public attention and an appropriate stakeholder involvement can aid to prevent problems and delays. The pursuit of climate goals and climate-friendly activities are also of public interest. Furthermore, the invasion of the Ukraine has led the European Union to rapidly reduce the dependency on Russian fossil fuels and to accelerate the clean energy transition (European Commission, 2022). In January 2023 new expansion targets for offshore wind energy in Europe were defined with an increase of 109 to 122 GW by 2030, 215 to 248 GW by 2040 and 281 to 354 GW by 2050 (Directorate-General for Energy, 2023). With increasing expansion targets, the end-of-life phase of offshore wind farms (OWF) will gain more importance. Simple replacement of low-capacity wind turbines with more efficient models and the reuse of the installed infrastructure is most likely not possible as the foundation structures and cables are not designed for turbines of larger sizes with higher capacities (Eckardt et al., 2022). Furthermore, increased hub heights and rotor diameter will require different turbine spacing. To reuse the area of decommissioned low capacity OWFs for the installation of new, more efficient OWFs, will most likely gain increasing attention soon, possibly regardless of whether they have already reached the end of their operational lifetime. Decision-makers, therefore, need to be enabled to make well-founded and comprehensible decisions on OWF decommissioning.

Until now, only very few OWFs have been decommissioned; the Swedish OWFs *Yttre Stengrund* (decommissioned in 2016) and *Utgrunden* (decommissioned in 2018), the Dutch OWF *Lely* (decommissioned in 2016), the Danish OWF *Vindeby* (decommissioned in 2017) and UK OWF *Blyth* (decommissioned in 2019) (4C Offshore, 2023d; offshoreWIND.biz, 2016a, 2016b, 2018; The Crown Estate, 2019). All of them had in common that they were small in turbine power (0.45 to 2 MW) and number (max. 11 turbines) and were located near shore (up to 4.2 km from shore) in shallow water (4C

Offshore, 2023a, 2023d, 2023c, 2023e, 2023b; offshoreWIND.biz, 2016a, 2016b, 2018; The Crown Estate, 2019). Due to their size and location, these decommissioning experiences are hardly transferable to the large-scale OWF decommissioning we will face in the future. The first large decommissioning phase of OWF with turbine capacities of 3 to 4 MW can be expected after 2030 (Eckardt et al., 2022). So far, there is no standardized procedure for the decommissioning of OWF across Europe (publication VII). In Germany, OWF usually have to be decommissioned completely; wind turbines and the offshore sub-station need to be dismantled, their foundations have to be cut below seabed and the scour protection layer as well as inter-array cables have to be removed (publication II). UK decommissioning programmes also outline that foundations need to be cut at or below seabed, but inter-array cables are aimed to be left in situ and the question whether scour protection layer is to be removed is often postponed to a later point in time (Britton, 2013; Drew, 2011; Stephenson, 2013).

Due to the lack of experiences, the decommissioning of OWF is associated with great uncertainties. The decommissioning processes are not well-known and there are no best-practices. Insufficient knowledge and understanding of the decommissioning processes make a well-founded selection among decommissioning alternatives very challenging, if not even impossible. Decommissioning alternatives might include different dismantling technologies (e.g., abrasive water jet cutting or diamond wire cutting) or scopes of decommissioning (e.g., leaving scour protection or sea cables in situ or cutting foundation structures above seabed) (publication VIII). Also, there is uncertainty of the impacts of different decommissioning alternatives. As offshore wind energy should be sustainable, the decommissioning should be associated with minor economic, environmental and social impacts. The impacts of different decommissioning alternatives are, however, currently not well investigated. Some of these uncertainties can be mitigated by establishing a knowledge base and others can be managed by applying appropriate analyses.

Multi-criteria decision analysis (MCDA) is a tool that supports decision-making processes by comparing alternatives considering different and even conflicting objectives (Geldermann & Lerche, 2014; Pedrycz et al., 2011). These objectives together with their attributes, that measure the achievement of the objectives, are referred to as decision criteria (Malczewski & Rinner, 2015). E.g., the objective that OWF decommissioning is associated with low greenhouse gas (GHG) emissions can be measured by the attribute CO_2-Equivalents. MCDA is a valuable tool for the analysis of sustainability as environmental, economic and social objects can be considered. A further advantage of MCDA is that the units of the decision criteria for measuring the achievement of the objects are omitted by transferring the criteria to dimensionless entities allowing for easier comparison, e.g., of t CO_2-Equivalents and hazard measure (Chen, 2000; Chou et al., 2008). If the ratings of alternatives (e.g., the amount of emitted GHG) and/or decision criteria (e.g., whether or how much one criterion is more important than another criterion) are associated with uncertainty, the literature suggests the application of fuzzy MCDA (Bellmann & Zadeh, 1970). Fuzzy MCDA consider fuzzy sets, which are a 'class of objects in which there is no sharp boundary between those objects that belong to the class and those that do not' (Bellmann & Zadeh, 1970). There is a great availability of (fuzzy) MCDA methods (Wątróbski et al., 2019) and selecting one of the methods for a certain decision problem is challenging. Accordingly, Polatidis et al. (2006) state, that 'there are no better or worse techniques, only techniques that fit better to a certain situation or not'. The appropriate method needs to be selected carefully, because it might affect ranking of the alternatives (Polatidis et al., 2006).

This thesis aims to support decision makers to make qualified and comprehensible decisions for sustainable OWF decommissioning. It addresses the analysis of selected decommissioning alternatives and the assessment of their sustainability, i.e., their GHG emissions, resource efficiency, costs, hazards and impact on benthic biodiversity, taking associated uncertainty into consideration. Due to the lack of information and experiences, first, a knowledge base was established: a stakeholder analysis was conducted to investigate their attitude towards OWF decommissioning (publication I), the legal framework (publication II) was researched, the system under investigation, i.e., a reference OWF, was defined (publication III) and decommissioning alternatives were developed (publication V and VIII). Thereafter, a framework was developed, that integrates stakeholder, sustainability and processes approaches (publication IV). It served as a basis for a MCDA. Decision criteria were defined, data for the assessment was collected and the alternatives were assessed (publications VI and VIII). Finally, different MCDA methods (the weighted sum model (WSM) in publication VIII and fuzzy SAW, fuzzy TOPSIS and fuzzy VIKOR in publication IX) were applied and the results were interpreted focusing on the comparison of the MCDA methods and the ranking of the decommissioning alternatives. In order to investigate the impacts of the weighting of the decision criteria on the ranking of the decommissioning alternatives an assessment with overweighted criteria was conducted (publication X).

CHAPTER 2

METHODOLOGY, METHODS AND DATA

2 Methodology, methods and data

In this chapter the collaboration of this dissertation with the research *SeeOff* is outlined first (chapter 2.1). In chapter 2.2 the methodology and methods of this study are presented. The assumptions for the calculation of species richness varied in the publications and are explained in chapter 2.3. Chapter 2.4 gives an overview of the sources for data and information required for the analyses.

2.1 Collaboration with the research project *SeeOff*

This dissertation was prepared in close collaboration with the research project *SeeOff* – *Strategieentwicklung zum effizienten Rückbau von Offshore-Windparks* (‘*Development of sustainable decommissioning strategies for offshore wind farms*’). The project had a duration of 3.5 years (01.11.2018–30.04.2022) and was funded by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag (grant number: 0324322). *SeeOff* aimed to support decision makers in developing sustainable strategies for the decommissioning of offshore wind farms (OWF). Therefore, decommissioning alternatives (referred to as ‘decommissioning scenarios’ in the *SeeOff* project) were developed and the processes of these decommissioning alternatives were analysed. In order to assess the sustainability of the decommissioning alternatives, economic (i.e., *costs*), environmental (i.e., *resource efficiency*, *greenhouse gas emissions* and *biodiversity*) and social (i.e., *hazards*) impacts were evaluated. The output of this research project is a handbook that is supposed to guide decision makers to develop and assess individual, project specific decommissioning alternatives (Eckardt et al., 2022).

For the duration of the research project *SeeOff* I was a research associate at the Hochschule Bremen, City University of Applied Sciences Bremen. In the research project I was responsible for the assessment of the sustainability of the decommissioning alternatives. So, the ‘*SeeOff* objective hierarchy for sustainable offshore wind farm decommissioning’ and the decision criteria (objectives and attributes) were developed and defined by myself or in close association with me, as in the case of the decision criteria *costs* and *hazards*. I analysed the environmental decision criteria. The economic and social decision criteria were analysed by colleges of the Hochschule Bremen, City University of Applied Sciences Bremen. They supplied the results which I subsequently used in the multi-criteria decision analysis (MCDA). As a consistent analysis of the decision criteria is crucial for the MCDA, it was my obligation to ensure that all decision criteria were analysed consistently. The same applies to the investigation of the decommissioning alternatives, i.e., the analysis of the decommissioning processes, which had to be consistent with the decision criteria. The structure of the decommissioning processes was developed in close association with myself. The procedure on how to investigate the decommissioning processes and which output was required, was established in consultation with myself. Some of the decommissioning processes at sea and on land were investigated by myself, the rest by my colleagues of the Hochschule Bremen, City University of Applied Sciences Bremen.

2.2 A guide to methodology and methods

Figure 1 gives an overview of the methodology and methods of this study. As the decommissioning of OWF is a topic, that is currently not well investigated, a basic knowledge base was established first. It includes a stakeholder analysis (publication I), the investigation of the legal basis (publication II), the description of a reference OWF (publication III) and the development of decommissioning alternatives (publications V and VIII). A framework that integrates sustainability, stakeholder and process approaches for sustainable decommissioning of OWF was developed (publication IV). The stakeholder analysis with the identification and categorisation of stakeholders is outlined in publications I and VIII. Key players were involved in the process and sustainability analysis. Within the process analysis, decommissioning processes were structured, different process options were identified, selected, parametrized and documented as well as combined to decommissioning alternatives. The procedure for the process selection and parametrization is outlined in detail in publication I. The procedure for process documentation and definition of decommissioning alternatives are described in publication VIII. The sustainability analysis encompasses the assessment of environmental, economic and social decision criteria. The approach for the selection of decision criteria is presented in publication I and the criteria weighting is outlined in publication VIII. The methods for the analysis of *resource efficiency* and *greenhouse gas (GHG) emissions* are outlined in publication VIII. The assessment of the impact of OWF decommissioning on the benthic *biodiversity* is more complex. The reason for this is a lack of environmental monitoring data as well the prediction on how the benthic biodiversity will evolve in the future. Therefore, I laid special focus on this analysis in publication VII. For the calculation of the species richness, different approaches and/or assumptions were applied in publications VII, IX and VIII. The differences are outlined in section 2.3. The results of the analyses of *costs* and *hazards* are important inputs for the MCDA. They were conducted by colleagues of the Hochschule Bremen, City University of Applied Sciences Bremen and are described in the report of the *SeeOff* project (Eckardt et al., 2022). For a holistic and comprehensible comparison of the decommissioning alternative, I applied MCDA. Within the research project *SeeOff* I applied the weighted sum model (WSM) (publication VIII). As OWF decommissioning, however, is associated with a lot of uncertainty, fuzzy MCDA methods are suitable. I, therefore, selected and applied three fuzzy MCDA methods (fuzzy SAW, fuzzy TOPSIS and fuzzy VIKOR) (publication IX). In order to test the influence of the weighting of the decision criteria on the ranking of the decision criteria, I overweighted the decision criteria, i.e., assigned much higher values for the individual criteria, and recalculated the ranks with the four MCDA methods (publication X).

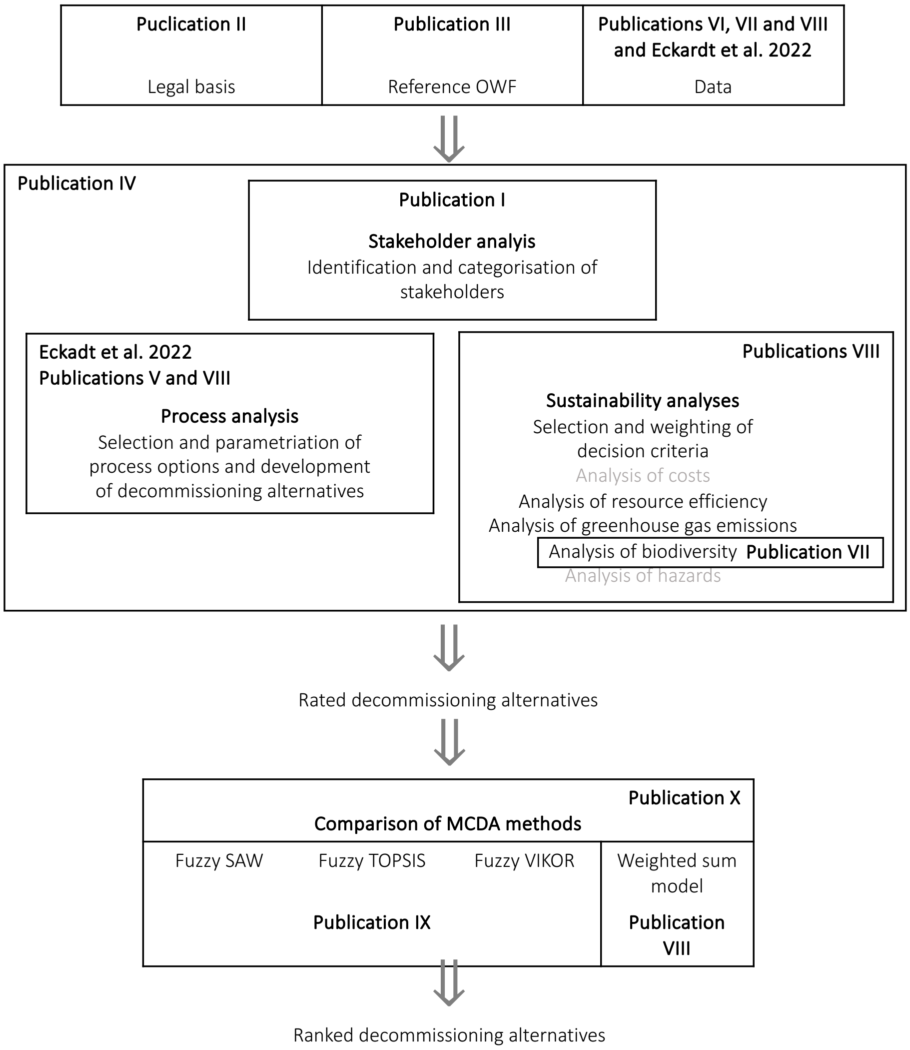

Figure 1: Overview of methodology and methods applied in the publications

2.3 Assumptions for the analysis of biodiversity

In all analyses, the decommissioning alternatives that affect the local *biodiversity* are fundamentally the same: (I) complete removal, i.e., cutting of the foundation structure below seabed or complete removal of the foundation structure including the removal of the scour protection layer (A_1 to A_5, A_7, A_9 and A_{10}), (II) cutting of foundation structure below seabed but leaving the scour protection layer in situ (A_6) and (III) cutting the foundation structure above seabed and leaving the scour protection layer in situ (A_8). However, underlying assumptions regarding the cutting heights of the foundations structure, foundation types considered or species richness calculation approaches differed throughout the publications (Table 1).

Table 1: Different assumptions underlying the calculations of the species richness in the three publications

Publication	Cutting heights above seabed	Species richness per	Foundation types
Publication VIII	3 m	water depth	monopiles gravity-base foundations jacket
Publication VII	5 m	distance from seabed	monopiles jacket
Publication IX	3 m	distance from seabed	monopiles jacket

In publications VIII and IX, for decommissioning alternative A_8 *WTG-FOU: Cut above seabed* it was assumed that the foundation structure was cut 3 m above seabed, in publication VII it was assumed it was cut 5 m above seabed. The monopiles of the reference OWF were assumed to have the cable entries at a height of 5 m above seabed. In this section, the wall thickness of the monopile is much higher than above and beyond, and would results in considerably higher cutting durations of the monopiles. As it was the aim to develop feasible decommissioning alternatives for publications VIII and IX, it was assumed, that if the monopile was cut above the seabed, it would rather be cut 3 m above seabed than 5 m. In publication VII it was the aim to analyse the impacts on the benthic species richness with the best data base available. There were 68 samples collected up to 3 m above seabed and 177 samples up to 5 m above seabed (publication VII, Table 3). So, in order to improve the analysis, in terms of making it more reliable, it was assumed that the foundation structure was cut 5 m above the seabed in publication VII.

To increase the sample size in publication VIII samples collect on gravity-base foundations were also considered. However, as analysis in publication VIII showed that the species richness was significantly higher at gravity-base foundation than at monopiles, gravity-base foundations were excluded for calculating species richness for the comparison of the decommissioning alternatives in publications VII and IX.

For the calculation of the species richness, different approaches regarding the consideration of the water depth were applied. In publication VIII species richness per water depth was calculated and a rather general top-down calculation was conducted calculating the species richness per water depth. It was assumed that the reference OWF had a mean water depth of 25 m and when cutting the foundation structure 3 m above seabed, all species found up to a water depth of 22 m would be maintained. For the calculation in publications VII and IX a more accurate bottom-up approach was applied. The species richness per distance from seabed was calculated accounting for different water depths.

2.4 Data and information

The data and information for the different analyses derived from literature research, expert interviews and workshops, online survey and the BISAR (Biodiversity Information System of benthic species at ARtificial structures) dataset on OWF associated benthic communities (publication V) accessed through the Alfred-Wegener-Institute AWI Biodiversity information system 'CRITTERBASE' (Teschke et al., 2022). For the MCDA the weighted decision criteria and results of the analysis of *GHG emissions*, *resource efficiency*, *biodiversity*, *costs* and *hazards* were used (Table 2).

Table 2: Sources of data and information required for the different analyses

Data / Information for	Source
Stakeholder analysis	Online survey
Process analysis	Literature research, expert interviews
Selection of decision criteria	Literature research, expert workshop
Weighting of decision criteria	Online survey
Analysis of greenhouse gases	Literature research, expert interviews
Analysis of resource efficiency	Literature research, expert interviews
Analysis of biodiversity	BISAR (Biodiversity Information System of benthic species at ARtificial structures) dataset on OWF associated benthic communities (publication V) accessed through the Alfred-Wegener-Institute AWI Biodiversity information system 'CRITTERBASE' (Teschke et al. 2022)
MCDA (Weighted sum model, Fuzzy SAW, Fuzzy TOPSIS and Fuzzy VIKOR)	Weighted decision criteria Analysis of greenhouse gas emissions, resource efficiency, biodiversity, costs and hazards

CHAPTER 3

PUBLICATIONS

3 Publications

This chapter presents the publications of my dissertation. My contribution to the publications is outlined in the division of work sections.

The publications were prepared for different journals and reports. The layout of the publications was unified for this dissertation. This especially concerns font formatting, table layout and colour of graphs.

Publication I

Spielmann V. and Eckardt S. (2022) Stakeholder analysis. Chapter 1.3 in Handbook of offshore wind farm decommissioning: Framework, technologies, logistics, processes, scenarios and sustainability, 25-28. https://doi.org/10.26092/elib/1539.

Content

In this publication a survey to identify relevant stakeholders of offshore wind farm decommissioning is presented. The stakeholders were group according to their profession and assigned to categories (key players, keep satisfied, keep informed and minimal effort) for offshore wind farm dismantling, logistics and disposal.

Division of work

I had the idea to perform the stakeholder analysis. In consultation with Silke Eckardt, I researched and adapted the methods, prepared, attended and evaluated the survey.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 90%
Experimental work and/or acquisition of (experimental) data:	ca. 100%
Data analysis and interpretation:	ca. 90%
Preparation of Figures and Tables:	ca. 100%
Drafting of the manuscript:	ca. 90%

Publication II

Scholz L., **Spielmann V.** and Eckardt S. (2022) Legal basis. Chapter 2.1.1 in Handbook of offshore wind farm decommissioning: Framework, technologies, logistics, processes, scenarios and sustainability, 38-45. https://doi.org/10.26092/elib/1539.

Content

This publication outlines the legal basis for the decommissioning obligations as well as the responsibility for the decommissioning of offshore wind farms in Germany. It also elaborates on the scope of decommissioning, i.e., the option of leaving components in situ.

I detected, that reference to the VwfG was missing and added it to the reference list.

Division of work

Silke Eckardt and myself defined the content and scope of this chapter. I conducted and evaluated literature research on the legal obligations of offshore wind farm decommissioning with the focus on partial decommissioning and compiled the results. To ensure legally compliant writing the first draft of this chapter was re-written by Lydia Scholz. I revised the chapter and reconciled changes with Lydia Scholz.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 60%
Experimental work and/or acquisition of (experimental) data:	ca. 65%
Data analysis and interpretation:	ca. 65%
Preparation of Figures and Tables:	Publication contains no figures and no tables
Drafting of the manuscript:	ca. 40%

Publication III

Spielmann V., Vajhøj J., Ebojie M., Rausch S. and Eckardt S. (2022) System description. Chapter 3.1 in Handbook of offshore wind farm decommissioning: Framework, technologies, logistics, processes, scenarios and sustainability, 70-82. https://doi.org/10.26092/elib/1539.

Content

This publication defines the system, structural components and boundaries of the investigated reference offshore wind farm and the base harbour. It also includes a mass balance of the reference offshore wind farm.

I detected that references to Lindvig (2010) and Per Aarsleff A/S 2018 were missing in the reference list and added them.

Division of work

The system and its boundaries were defined by all authors. The structural components were specified in close reconciliation of all authors. Mandy Ebojie and Jesper Vajhøj had the lead for the offshore wind turbine generator, transition piece and monopile. I lead the sub-chapters on the scour protection, inter-array cables, export cable and offshore substation. Sven Rausch specified the base harbour. The mass balance was compiled by myself in close consultation with Sven Rausch.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 60%
Experimental work and/or acquisition of (experimental) data:	ca. 60%
Data analysis and interpretation:	ca. 75%
Preparation of Figures and Tables:	ca. 60%
Drafting of the manuscript:	ca. 60%

Publication IV

Spielmann V., Brey T., Dannheim J., Vajhøj J., Ebojie M. G., Klein J. and Eckard S. (2021) Integration of sustainability, stakeholder and process approaches for sustainable offshore wind farm decommissioning. Renewable and Sustainable Energy Reviews, 147, 111222. https://doi.org/10.1016/j.rser.2021.111222.

Content

This paper outlines a framework for integrating sustainability, stakeholder and process approaches for sustainable offshore wind farm decommissioning. It comprises a stakeholder approach, where relevant stakeholders are identified and analysed, a sustainability approach, in which objectives for sustainable offshore wind farm decommissioning are defined, and a process approach, including the selection, documentation and parametrization of decommissioning processes.

Division of work

I had the idea and developed the concept for the integration of stakeholder, sustainability and process approaches. In consultation with Silke Eckardt, I developed the structure for the sustainability profiles and defined the environmental decision criteria. I guided my co-authors to define the social (Mandy Ebojie) and the economic decision criteria (Johanna Klein). I was responsible for, carried out and evaluated the stakeholder survey. The overall decommissioning process was developed by myself, the operational process was documented by Jesper Vajhøj (both in consultation with Silke Eckardt). I had the lead in writing the publication.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 90%
Experimental work and/or acquisition of (experimental) data:	ca. 85%
Data analysis and interpretation:	ca. 100%
Preparation of Figures and Tables:	ca. 100%
Drafting of the manuscript:	ca. 90%

Publication V

Birchenough S., Boon A., Braekman U., Brey T., Brzana R., Buyse J., Capet A., Carey D., Causon P., Coolen J. W. P., Dannheim J., Dauvin J.-C., Davies P., De Mesel I., Degraer S., Gill A., Guida V., Harrald M., Hutchison Z., Janas U., Kloss P., Krone R., Labrune C., Laverre M., Lefaible N., Mavraki N., Muxika I., O`Beirn F., Pezy, J.-P., Raoux A., Rasser M., Sheehan E., **Spielmann V.**, Trager E., Vanaverbeke J., Vinagre P. and Wilding T. (2021) Develop the scientific basis for assessing the conservation of benthic habitats beyond the exploitation phase of marine renewable energy installations (ToR d). In WORKING GROUP ON MARINE BENTHAL AND RENEWABLE ENERGY DEVELOPMENT (WGMBRED). ICES Scientific Reports, 3 (63), 8-11

Content

The report of the Working Group on Marine Benthal and Renewable Energy Development (WGMBRED) intends to raise the scientific exchange and to improve research associated with benthal renewable energies. Chapter 4 focuses on the impacts during and after the decommissioning of offshore wind farms by assessing different decommissioning scenarios.

Division of work

The aforementioned authors have contributed to different chapters of the report. However, not all authors have necessarily participated at the work of this chapter.

I consulted in an interview on the development of the decommissioning scenarios and technical issues of decommissioning. I actively participated at the sessions of the working group meeting when the scientific questions were worked on.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 20%
Experimental work and/or acquisition of (experimental) data:	ca. 20%
Data analysis and interpretation:	ca. 30%
Preparation of Figures and Tables:	ca. 0%
Drafting of the manuscript:	ca. 0%

Publication VI

Dannheim J., Kloss P., Vanaverbeke J., Mavraki N., Zupan M., **Spielmann V.**, Degraer S., Silvana N.R., Birchenough S. N. R., Janas U., Sheehan E., Teschke K., Gill A. B., Hutchison Z., Carey D. A., Rasser M., Buyse J., van der Weide B., Bittner O., Causon P., Krone R., Faasse M. and Coolen J. W. P. (in preparation) Biodiversity Information System of benthic species at ARtificial structures (BISAR)

Content

This publication introduces the open access data sharing platform 'Biodiversity Information System of benthic species at ARtificial structures' (BISAR). It contains data on soft and hard substrate benthic macrofauna collected at 17 artificial structures (offshore wind farms, oil and gas platforms, a research platform and geogenic reefs) in the North Sea.

The final version for submission is in preparation. The draft included in this work is from June 2023.

Division of work

I contributed to the data quality check. Ninon Mavraki, Mirta Zupan and myself defined and wrote section 6 usage notes for BISAR.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 0%
Experimental work and/or acquisition of (experimental) data:	ca. 0%
Data analysis and interpretation:	ca. 15%
Preparation of Figures and Tables:	ca. 0%
Drafting of the manuscript:	ca. 15%

Publication VII

Spielmann V., Dannheim J., Brey T. and Coolen, J. W. P. (2023) Decommissioning of offshore wind farms and its impact on benthic ecology. Journal of Environmental Management, 347, 1 December 2023, 119022. https://doi.org/10.1016/j.jenvman.2023.119022.

Content

In this paper the impact of offshore wind farm decommissioning on the epibenthic macrofauna community is analysed. The focus lays upon the partial vs. complete decommissioning of the foundation structure and scour protection layer. We analyse how much epibenthic macrofauna species richness would be maintained for three decommissioning scenarios (complete removal, leaving the scour protection layer in situ and cutting the foundation structure 5 m above seabed in combination with leaving the scour protection layer in situ).

Division of work

I had the idea and developed the concept of this publication in association with the co-authors. Data selection and processing was carried out by myself in consultation with the co-authors. Data analysis was carried out by myself, but in close consultation with Joop Coolen. I had the lead in writing the paper, but all co-authors revised it and made suggestions for improvement.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 80%
Experimental work and/or acquisition of (experimental) data:	ca. 95%
Data analysis and interpretation:	ca. 90%
Preparation of Figures and Tables:	ca. 100%
Drafting of the manuscript:	ca. 90%

Publication VIII and Erratum

Spielmann V., Ebojie M., Vajhøj J., Rausch S. and Eckardt S. (2022) Assessment of sustainable strategies for offshore wind farm decommissioning and Discussion. Excerpts of chapters 4 and 5 in Handbook of offshore wind farm decommissioning: Framework, technologies, logistics, processes, scenarios and sustainability, 141-235. https://doi.org/10.26092/elib/1539.

Content

Chapter 4 'Assessment of sustainable strategies for offshore wind farm decommissioning' introduces the objectives for sustainable offshore wind farm decommissioning, the approach for the assessment of decommissioning alternatives and the decommissioning alternatives. The methods for calculating the decision criteria and the results as well as the multi-criteria decision analysis applied and the ranking of the alternatives are also presented in this chapter. In chapter 5 'Discussion' the methods and quality of the research output as well as the partial decommissioning alternatives are reviewed. Transferability of the dismantling techniques, logistics and decommissioning processes as well as the assessment approach on other offshore wind farms or components is discussed. Please note that this dissertation includes those sub-chapters only to which I contributed considerably.

When revising the results of the multi-criteria decision analysis, three mistakes came to my attention: (i) wrong values for the point of the pairwise comparison were entered in table 65 (ii) the weights of the decision criteria *resource efficiency* and *biodiversity* were interchanged for the calculations and (iii) the wrong number of points for the criteria fulfilment of *resource efficiency* were assigned to alternative A_6. I recalculated the multi-criteria decision analysis and wrote an Erratum.

I also detected that references were missing and added the references of Alstorm (2015), Arup (o.J.) and European Commission (2015) to the reference list.

Division of work

I developed the assessment approach in close consultation with Silke Eckardt. I defined the environmental decision criteria, researched and developed the methods to calculate them, carried out the calculations and assessments. My colleagues were responsible for the economic and social decision criteria and provided the results for the calculation of the decision scores. The decommissioning alternatives were compiled by myself, Jesper Vajhøj, Mandy Ebojie, Johanna Klein, Janina Bösche and Silke Eckardt, but also in consultation with other partners of the research project *SeeOff*. I carried out the multi-criteria decision analysis and assessed the results, all in consultation with Silke Eckardt and Armin Varmaz. The critical review of the methods, quality of research results and partial decommissioning scenarios were written by myself with support of Mandy Ebojie and Janina Bösche discussing the economic and social decision criteria. The sub-chapter on the transferability of dismantling techniques, logistics and decommissioning processes were written by Mandy Ebojie and myself. I had the lead on the transferability of the assessment approach.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 90%
Experimental work and/or acquisition of (experimental) data:	ca. 100%
Data analysis and interpretation:	ca. 100%
Preparation of Figures and Tables:	ca. 100%
Drafting of the manuscript:	ca. 95%

Publication IX

Spielmann V., Eckardt S., Varmaz A. (submitted) Multi-criteria decision analysis for sustainable offshore wind farm decommissioning. Submitted to the Journal of Industrial Ecology on 22 November 2023

Content

In this paper three fuzzy multi-criteria decision analysis methods (fuzzy SAW, fuzzy TOPSIS and fuzzy VIKOR) are selected and applied to evaluate the sustainability of different offshore wind farm decommissioning alternatives. The alternatives and their environmental, economic and safety-related impacts are compared. The methodical differences of the multi-criteria decision analysis are discussed to account for variations in the ranking of the alternatives. This study also demonstrates the potential of combining multi-criteria decision analysis with life-cycle assessment.

Division of work

I had the idea to compare the offshore wind farm decommissioning alternatives using fuzzy multi-criteria decision analysis methods. I selected the multi-criteria decision analysis methods and applied them to the use case. The application and assessment of the multi-criteria decision analysis methods were carried out by me, but in consultation with Armin Varmaz. I had the lead on writing the paper, but had it revised and improved by the co-authors.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 90%
Experimental work and/or acquisition of (experimental) data:	ca. 80%
Data analysis and interpretation:	ca. 100%
Preparation of Figures and Tables:	ca. 100%
Drafting of the manuscript:	ca. 80%

Publication X

Spielmann V. (in preparation) Impact of decision criteria weighing on the ranking of offshore wind farm decommissioning alternatives. (to be submitted to European Journal of Operational Research)

Content

The previous publications focused on the comparison of the decommissioning alternatives (publication VIII) and/or multi-criteria decision analysis methods (publication IX). This analysis focuses on the impacts of decision criteria weighting on the ranking of the decommissioning alternatives. Therefore, ranks of the alternatives were recalculated with the MCDAs fuzzy SAW, fuzzy TOPSIS, fuzzy VIKOR and WSM using overweighted decision criteria, i.e., one criterion receives much higher weighting than the other criteria.

Division of work

I had the idea, performed the analysis, assessed the results and wrote the manuscript by myself.

Contribution to the publication

Contribution of the candidate in % of the total work load (up to 100% for each of the following categories):

Experimental concept and design:	ca. 100%
Experimental work and/or acquisition of (experimental) data:	ca. 100%
Data analysis and interpretation:	ca. 100%
Preparation of Figures and Tables:	ca. 100%
Drafting of the manuscript:	ca. 100%

I Stakeholder analysis

Spielmann V[a, b] and Eckardt S[a]

Chapter 1.3 in Handbook of offshore wind farm decommissioning: Framework, technologies, logistics, processes, scenarios and sustainability, 2022, 25-28. https://doi.org/10.26092/elib/1539

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1.3 Stakeholder analysis

A large number of different stakeholders are involved in the decommissioning of offshore wind farms (OWF). The licensees of OWF, who are responsible for preparing the decommissioning plan, and the regulatory authority, which approves the decommissioning plan, are arguably the most significant stakeholders in OWF decommissioning (BSH 2015a). In addition, however, many organisations are directly or indirectly involved in the planning, approval and/or implementation of decommissioning.

As part of the research project *SeeOff* a survey wmias conducted to identify relevant stakeholders of OWF decommissioning. The survey was conducted using the online tool SurveyMonkey from SurveyMonkey Inc. (San Mateo, California, USA www.surveymonkey.com). The survey was active for 3 weeks during the period 24 May 2019 to 16 June 2019. A total of 111 people responded to the survey. 30 responses could not be used and were removed, so that the analysis is based on a total of 81 responses.

Table 4 provides an overview of stakeholders involved in OWF decommissioning. The stakeholders were structured into main groups and subgroups. At least one stakeholder from each main group, except for certifiers and inspectors, participated in the survey. Almost half of the respondents stated that they were directly (44.4 %) and indirectly (49.4 %) involved in the planning, approval and/or implementation of the dismantling of OWF.

The respondents were asked to rate how important knowledge in various topics is for efficient decommissioning. The assessment was made on a scale of 1 to 10, with 1 being "not relevant" and 10 being "very relevant". Alternatively, respondents could indicate that they had no opinion on the importance of the topic. For the stakeholders surveyed, knowledge in the area of environmental aspects is of particular importance (Figure 20). However, knowledge of economic and occupational safety aspects is also relevant. Knowledge regarding acceptance was again rated very broadly, so that this aspect was not rated as very important by all stakeholders.

Table 4: Main and subgroup of stakeholders directly or indirectly involved in offshore wind farm decommissioning.

Main stakeholder group	Stakeholder subgroup
Operator	Offshore wind farm operator
	Grid connection operator
Planning and service company	OWF project planning
	Service Construction, operation and maintenance
	Divers
	Cable ladder
	HSE service provider

Main stakeholder group	Stakeholder subgroup
Dismantling/repowering companies	Dismantling ashore & repowering
	Dismantling offshore
Manufacturer	Offshore wind turbine
	Transition Piece
	Topside offshore substation
	Topside Offshore Converter Platform
	Foundation structures (offshore wind turbine)
	Foundation structures (offshore substation)
	Foundation structures (offshore converter platform)
	Submarine cable
Suppliers	---
Ministry, Authority	Ministry
	Approval authority
	Nature conservation authority
	Business development
Certifier, inspector	---
Logistics company	Maritime logistics
	Port operator & management
	Onshore logistics
Disposal company	---
Consultancy	Legal advice
	Auditing firm
	Environmental planning offices
	HSE
	Acceptance
	Customs
	Engineering office
Financial service provider	Bank
	Insurance
Association/stakeholder	Fisheries Association
	Tourism Association
	Nature Conservation Association
	Industry association
	Stakeholder North Sea
	Stakeholders in the waste management/recycling industry
	Port
Research institution / universities	Offshore wind energy
	Maritime logistics
	Environment
	Fishing

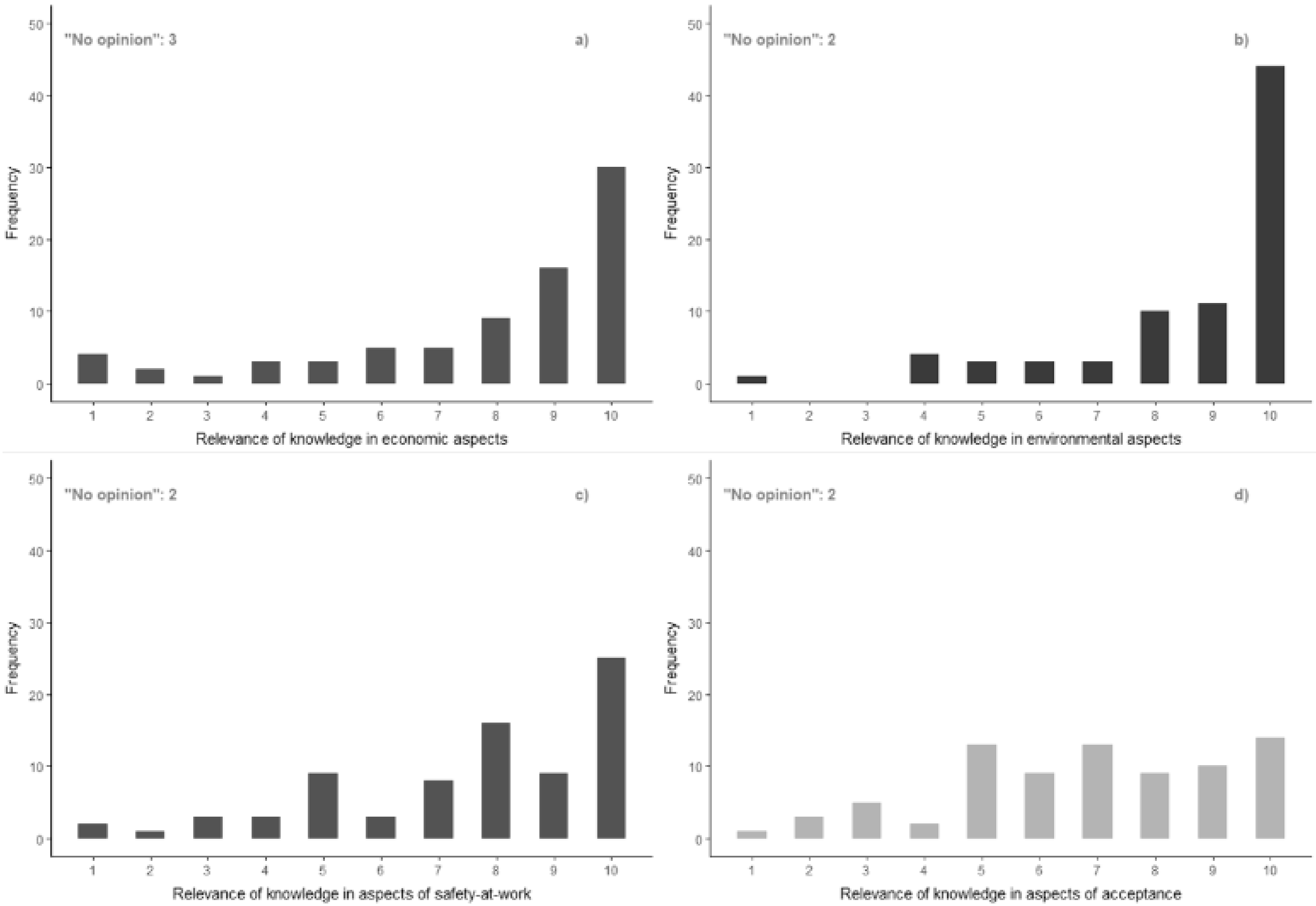

Figure 20: Importance of knowledge regarding a) economic aspects, b) environmental aspects, c) occupational safety aspects and d) acceptance aspects in frequency. (1 = not significant to 10 = very significant and "no opinion")

A stakeholder analysis was also carried out to determine the stakeholder categories for the dismantling, logistics and recycling of OWF. Based on the stakeholder categories, strategies for dealing with the respective stakeholders can be derived. The stakeholder categories according to Wadenpohl (2010) are:

- **Key player**: The stakeholders in this group not only have a great interest in the project, but also the power to influence the project. These stakeholders should be given special attention.
- **Keep satisfied**: The stakeholders in this group have great power to influence the project, but otherwise have little interest in it.
- **Keep informed**: The stakeholders in this group are very interested in the project, but (initially) have little or no influence on it.
- **Minimal effort**: The stakeholders in this group are neither interested in the project nor do the stakeholders have the power to significantly influence the project.

The methodological procedure for stakeholder analysis can be found in the publication (Spielmann et al. 2021).

It can be seen that various key players can be taken into account, especially for dismantling. In addition to operators and ministries/authorities, planning/service companies, dismantling/repowering companies, manufacturers and consulting companies can also be classified as key players for dismantling and logistics, and logistics companies for logistics. For disposal, only two key players were identified, namely disposal companies and dismantling/repowering companies (Table 5).

Table 5: Stakeholder categories (Key Player, Keep informed and Minimal effort) per main stakeholder group for dismantling, logistics and disposal of OWF (n=number of respondents per main stakeholder group).

Main stakeholder group	n	Disassembly	Logistics	Disposal
Operator	17	Key Player	Key Player	Keep informed
Planning / service company	7	Key Player	Key Player	Minimal effort
Dismantling/repowering companies	5	Key Player	Key Player	Key Player
Manufacturer	1	Key Player	Key Player	Minimal effort
Suppliers	3	Minimal effort	Minimal effort	Minimal effort
Ministry, Authority	10	Key Player	Minimal effort	Minimal effort
Logistics company	7	Keep informed	Key Player	Minimal effort
Disposal company	2	Not assignable	Keep informed	Key Player
Consultancy	10	Key Player	Key Player	Minimal effort
Financial service provider	3	Minimal effort	Minimal effort	Minimal effort
Association/stakeholder	7	Minimal effort	Minimal effort	Minimal effort
Research institution / universities	9	Minimal effort	Minimal effort	Minimal effort

References

BSH (2015a): Standard Konstruktion Mindestanforderungen an die konstruktive Ausführung von Offshore-Bauwerken in der ausschließlichen Wirtschaftszone (AWZ). 1. Fortschreibung. Hamburg, Rostock. https://www.bsh.de/DE/PUBLIKATIONEN/_Anlagen/Downloads/Offshore/Standards-DE/Standard-Konstruktion.pdf;jsessionid=3E4D5C06FD1F1D4336B60116283A29BD.live21301?__blob=publicationFile&v=12 [Access: 09.07.2019].

Spielmann, V.; Brey, T.; Dannheim, J.; Vajhøj, J.; Ebojie, M.; Klein, J.; Eckardt, S. (2021): Integration of sustainability, stakeholder and process approaches for sustainable offshore wind farm decommissioning. In: *Renewable and Sustainable Energy Reviews* 147, p. 111222. DOI: 10.1016/j.rser.2021.111222.

Spyroudi, A. (2021): End-of-Life planning in offshore wind. Catapult Offshore Renewable Energy. https://ore.catapult.org.uk/wp-content/uploads/2021/04/End-of-Life-decision-planning-in-offshore-wind_FINAL_AS-1.pdf.

Wadenpohl, F. (2010): Stakeholder Management bei grossen Verkehrsinfrastrukturprojekten. Dissertation. ETH Zürich, Zürich.

II Legal basis

Scholz L[a], Spielmann V[a, b] and Eckardt S[a]

Chapter 2.1.1 in Handbook of offshore wind farm decommissioning: Framework, technologies, logistics, processes, scenarios and sustainability, 2022, 38-45. https://doi.org/10.26092/elib/1539

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2.1 Legal framework conditions

2.1.1 Legal basis

2.1.1.1 Applicability of the Convention on the Law of the Sea and German law

The decommissioning of offshore wind farms (OWF) is subject to German law as well as international maritime law, in particular the United Nations Convention on the Law of the Sea (UNCLOS) as the "Constitution of the Seas", which regulates the use of the Exclusive Economic Zone (EEZ) by the coastal states and refers to other international law that must be observed.

The law of the Federal Republic is initially only applicable to the German territory, which includes the territorial sea. According to Art. 3 UNCLOS, each state has the right to determine the breadth of its territorial sea up to a limit which may not be more than 12-nautical-miles from the baselines entered by the coastal state in officially recognised large-scale nautical charts (Art. 3 UNCLOS). The Federal Republic has made use of this right, so that German laws and German administrative action extend directly to this area within the 12-nautical-mile-zone. Furthermore, in view of the federal structure of the Federal Republic, it must be taken into account that every part of the national territory is not only part of the federal territory, but at the same time part of the national territory. Accordingly, the territorial sea is not exclusively federal territory, but part of the respective coastal federal state. Thus, the respective state law is also applicable in the territorial sea.

According to Art. 55 UNCLOS, the EEZ, in which offshore wind farms are usually located, is designated as a maritime area that is to be located behind the territorial sea. Unlike the territorial sea, the EEZ is no longer part of the national territory, so that the applicability of German laws as well as the actions of German authorities require a positive determination (Art. 55 UNCLOS). Art. 56 UNCLOS allows the exercise of sovereign rights, for example, for the purpose of exploiting the natural resources found there, for energy production and for taking environmental protection measures. In the EEZ, the coastal state has the exclusive right to construct and to authorise and regulate the construction, operation and use of installations and structures for the purposes provided for in Art. 56 and for other economic purposes (Art. 60 UNCLOS).

To what extent the Federal Republic makes use of its right under Art. 56 UNCLOS and exercises sovereign rights in the form of legislation and administrative action based thereon, the corresponding facts are subject to German law. This includes the application of the Basic Law for the Federal Republic of Germany (Grundgesetz - GG), in particular the fundamental rights enshrined therein. For it follows from Article 1 (3) and Article 20 of the Basic Law that a commitment to German fundamental rights is to be assumed wherever German state power is exercised. Construction and demolition measures, insofar as they involve the exercise of German state power, therefore also fall within the material scope of the GG in the EEZ (Ehlers 2013; Maurer 2012). Official orders therefore always require a legal basis and must not violate the fundamental rights of the plant operator or owner.

The federal laws and ordinances applicable in the German EEZ on which official orders can be based also include those regulating the construction, operation and decommissioning of offshore wind turbines. These include the ordinance on installations seaward of the boundary of the German Territorial Sea (Seeanlagenverordnung - SeeAnlV), the act for the development and promotion of offshore wind energy (Offshore Wind Energy Act - WindSeeG) and also the act on the tasks of the Federal Government in the field of maritime navigation (Seeaufgabengesetz - SeeAufgG).

2.1.1.2 Legal basis for the decommissioning obligation

The legal basis for the decommissioning of OWF is derived from the SeeAnlV and the WindSeeG. It is important to note that the SeeAnlV applies to installations commissioned by 31 December 2020, whereas the WindSeeG applies to installations commissioned after 31 December 2020.

SeeAnlV

According to § 1 para. 2 SeeAnlV, the SeeAnlV, which came into force in 1997, applies to the construction, operation and modifications of installations in the EEZ of the Federal Republic of Germany and on the high seas. The prerequisite is that the owner is a German resident in the Federal Republic of Germany or, in the case of commercial companies or legal entities, that the registered office of the company is in Germany.

Wind turbines meet the requirements of the definition of installation set out in § 1 para. 2 SeeAnlV:

For the purposes of this Ordinance, installations are all structural or technical facilities, including structures and artificial islands, which are fixed or which are floating for more than a short-term purpose, as well as the respective ancillary facilities required for their construction and operation, which are

1) the generation of energy from water, current and wind
2) the transfer of energy from water, current and wind
3) other economic purposes or
4) marine studies.

Installations for the "generation of energy" within the meaning of No. 1 are offshore wind turbines. No. 2 defines the transmission of electricity to the shore (§ 1 marginal no. 9 (Theobald et al. 2021).

Pursuant to para. 2, necessary ancillary facilities also fall under the term "installation". Such ancillary facilities for the operation of wind turbines can be "e.g. platforms during the construction phase, rescue facilities, helicopter landing decks, wind farm-internal cabling or transformer platforms and, if applicable, measuring masts or installations" (§ 1 marginal no. 13. (Theobald et al. 2021) In contrast, grid connection lines (with converter platforms) are independent installations (§ 1 marginal no. 13). (Theobald et al. 2021)

§ 2 para. 1 SeeAnlV made the construction and operation of installations within the meaning of § 1 para. 2 sentence 1 nos. 1 and 2 SeeAnlV as well as the substantial modification of such installations or their operation subject to approval until 30.1.2012 and subject to planning approval with effect from 31.1.2012. At present, therefore, there are both OWF that are based on a permit as well as offshore installations that have been decided by means of a planning approval. The competent authority is the Federal Maritime and Hydrographic Agency (BSH).

If the planning approval has expired or the permit has lapsed, the installations must be removed in accordance with § 13 para. 1 SeeAnlV. This is pursuant with § 60 para. 3 UNCLOS, according to which all abandoned or no longer used installations or structures must be removed in order to ensure the safety of navigation.

On the basis of § 2 para. 1 SeeAnlV, the BSH has approved or granted planning approval for wind turbines existing in the German EEZ and commissioned before 31 December 2020.

WindSeeG

Pursuant to Article 1(1)(3), the WindSeeG regulates the licensing, construction, commissioning and operation of offshore wind turbines, other energy generation facilities and offshore connection lines, insofar as they are commissioned after 31 December 2020.

The term offshore wind turbine is defined in § 3 No. 7 as:

> *'every installation to generate electricity from wind energy which has been constructed at sea at a distance of at least three nautical miles measured seawards from the coastline of the Federal Republic of Germany; the coastline shall be taken to be the coastline depicted in Map Number 2920 German North Sea Coast and Adjacent Waters, 1994 edition, XII., and in Map Number 2921 German Baltic Coast and Adjacent Waters, 1994 edition, XII. of the Federal Maritime and Hydrographic Agency, scale of 1:375 000'.*

Pursuant to § 45 WindSeeG, the construction and operation of facilities as well as the substantial modification of such facilities or their operation require planning approval by the BSH. § 58 para. 1

WindSeeG regulates the removal of facilities if the planning approval decision has become invalid. The legal situation under the WindSeeG corresponds to the legal situation under the SeeAnlV.

If the BSH orders the decommissioning obligation in the planning approval decision on the basis of § 58 para. 1 WindSeeG, this order forms the legal basis for the dismantling obligation. If the BSH does not order decommissioning in the decision, the obligation follows from § 58(1) WindSeeG.

Official order for dismantling

As the competent authority, the BSH may order the decommissioning obligation in the notice of approval or planning approval decision on the basis of § 13 para. 1 SeeAnlV or § 58 para. 1 WindSeeG. In doing so, the authority must take the requirements of regional planning and sectoral planning for the North Sea and the Baltic Sea into account. On the basis of § 17 of the Federal Regional Planning Act, regional planning plans for the North Sea and the Baltic Sea were initially issued in 2009, which stipulate in their respective sections 3.5.1 that offshore wind turbines must be decommissioned after they have ceased to be operational. The decommissioning obligation is also regulated in the Spatial Development Plan (Raumordnungsplan) 2021 for the German EEZ in the North Sea and the Baltic Sea (section 2.2.1), which is now in force. More specific planning requirements are contained in the respective applicable land development plan. For example, the Site Development Plan (Flächenentwicklungsplan) 2019 consistently stipulates that offshore wind turbines must be dismantled once they have ceased to be operational.

If the BSH has ordered dismantling in the approval or planning approval decision, this order is to form the legal basis for the decommissioning obligation. After the decision has become final, the provisions contained therein are to take precedence over the abstract-general statutory provisions of the SeeAnlV and the WindSeeG. If the decommissioning is not specifically regulated in a notice of approval or planning approval decision, the decommissioning obligation follows directly from § 13 para. 1 SeeAnlV or § 58 para. 1 WindSeeG.

2.1.1.3 Responsibility for decommissioning

The responsibility for fulfilling the obligations arising from the SeeAnlV and the WindSeeG follows from § 15 para. 1 SeeAnlV and, with identical wording, from § 56 para. 1 WindSeeG. Responsible parties are:

1) 'the addressee of the planning approval decision or the planning consent, or in case of legal persons and commercial partnership, the individuals appointed to represent them by statute, by-laws or articles of association,

2) the operator of the installation, or in case of legal persons and commercial partnership, the individuals appointed to represent them by statute, by-laws or articles of association, and
3) the individuals appointed to manage or supervise the operation or parts of the operation, within the scope of their responsibilities and powers.’

If the BSH has ordered the dismantling obligation in the planning approval decision, the responsibility of the addressee within the meaning of No. 1 follows directly from the planning approval decision. In this case, in the event of a difference of persons, the operator of the installation (No. 2) and persons within the meaning of No. 3 shall also remain obliged to decommission the installation.

2.1.1.4 Scope of the decommissioning

The legal scope of decommissioning is defined in § 13 SeeAnlV and § 58 WindSeeG with corresponding references to the relevant international law. As a result, the regulations described in detail below require a case-by-case consideration, so that no legally robust statements can be made on the exact technically defined scope.

If the BSH has issued or is issuing orders on the scope of decommissioning on the basis of the statutory regulations, these must be followed. As a rule, this provides legal certainty because, in contrast to an abstract-general regulation in the law, a decision is made on a case-by-case basis.

Necessity pursuant to § 13 para. 1 SeeAnlV and § 58 para. 1 WindSeeG

With regard to the scope of decommissioning, § 13 para. 1 SeeAnlV stipulates that the installations must be removed to the extent required by the interests specified in § 5 para. 6 or § 7 SeeAnlV. The term "installation" as defined in § 1 para. 2 SeeAnlV (see above) applies, which covers wind turbines as well as the ancillary facilities required for their construction and operation. Comparable in terms of substantive law, § 58 para. 1 WindSeeG provides for the removal of facilities to the extent required by the interests specified in § 48 para. 4 nos. 1 to 4. The term "facilities" is legally defined in accordance with § 44 WindSeeG, whereby, in addition to offshore wind turbines, facilities also include ‘installations to transmit electricity from offshore wind energy installations including the technical and structural ancillary facilities (facilities) required to construct and operate the installations’.

These concerns, which are decisive for the scope of decommissioning, include, for example, the safety and efficiency of traffic and the security of national and alliance defence, as well as the protection of the marine environment and concerns arising from other public-law regulations.

A hazard to the safety and efficiency of traffic could result from parts of the installation that have not been completely removed, e.g. if fishing trawl nets become entangled and cause fishing vessels to capsize (§ 13 Rn. 1Theobald et al. 2021).

The scope of dismantling also depends on the "other public law provisions" (see above), which also include spatial and sectoral planning. These include the ordinance on spatial planning in the German WWZ in the North Sea (Verordnung über die Raumordnung in der deutschen ausschließlichen Wirtschaftszone in der Nordsee - AWZ Nordsee-ROV). The 2009 spatial plans for the North Sea and the Baltic Sea, which stipulate in their respective sections 3.5.1 that offshore wind turbines must be decommissioned after they have ceased to be operational. If decommissioning causes greater adverse environmental impacts than remaining in place, it shall not be carried out in whole or in part unless decommissioning is necessary for reasons of safety and efficiency of traffic. In the Spatial Development Plan 2021 for the German EEZ in the North Sea and the Baltic Sea now in force, sub-section 2.2.1 (2) also stipulates that such fixed installations must be decommissioned at the end of their operational life. It follows from the explanation to subsection (2) that this includes cables.

According to this, OWF inter-array cables (IAC) must also be removed as a matter of principle in accordance spatial planning regulations, even though they are buried in the seabed. The directive on offshore installations to ensure the safety and efficiency of shipping (Richtlinie Offshore-Anlagen zur Gewährleistung der Sicherheit und Leichtigkeit des Schiffverkehrs), issued by the directorate general for waterways and shipping (Generaldirektion Wasserstraßen und Schifffahrt), also calls for the removal of submarine cables. Although this directive does not constitute a legal regulation, it can be used by authorities and courts to interpret the legal regulations on the scope of dismantling and then has a binding effect through the principle of equal treatment enshrined in Article 3 of the Basic Law for the Federal Republic of Germany.

From the concerns to be taken into account during decommissioning, it is derived from the literature that complete removal of the installation does not have to take place in every case, especially if installations or parts of installations do not pose a risk to the objects of protection referred to in the SeeAnlV (and thus also of the WindSeeG). It may be appropriate to refrain from decommissioning individual parts of the installation if this is less harmful to the marine environment. Harmless turbine components could take over the function of reefs and offer marine life such as plants, mussels and small animals a settlement and protection area. (§ 58 Rn. 12Säcker 2017) (Säcker 2017; § 13 Rn. 1.Theobald et al. 2021). This view is supported by the wording of § 13 para. 1 SeeAnlV and § 58 para. 1 WindSeeG. The installations or facilities are to be removed "to the extent required by the interests mentioned (...)". The legislator thus only assumes that the decommissioning is limited to what is necessary. It cannot be determined with legal certainty to what extent this view can be successfully held against the obligation of complete decommissioning. There is no case law on this topic to date.

Generally recognised international standards pursuant to § 13 para. 2 SeeAnlV and § 58 para. 2 WindSeeG

Moreover, according to § 13 para. 2 SeeAnlV and § 58 para. 2 WindSeeG, the generally recognised international standards for removal are to be taken into account as a minimum standard.

This corresponds to Art. 60 section 3 UNCLOS. Here it says: "...taking into account any generally accepted international standards established in this regard by the competent international organization". The international organisation in this case is the International Maritime Organization, which is a specialised agency of the United Nations. With Resolution A.672(16) "Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the EEZ" of 1989, the IMO has developed such rules and standards (International Maritime Organization - IMO 1989). According to Art. 60 section 3 UNCLOS, the UNCLOS member states are obliged to take these recommendations into account when regulating decommissioning measures. The Federal Republic of Germany has complied with this obligation by means of § 13 para. 2 SeeAnlV and § 58 para. 2 WindSeeG. According to Resolution A 672 (16), all abandoned or no longer used turbines in water depths of less than 100 m are to be completely removed (IMO 1989); § 13 marginal no. 3 (Theobald et al. 2021). However, the regulations allow a State to determine whether the installation or structure may remain in place, in whole or in part, if it is approved for a new use or does not cause unacceptable interference with other uses of the sea. Other reasons for partial retention may be that decommissioning is technically not feasible, extreme costs would be incurred or unacceptable risks to personnel or the marine environment exist. However, according to section 3.6, if removal is not complete, it must be ensured that the water column above the remaining structure is 55 m to ensure safe navigation. However, OWF in the German EEZ at a water depth of more than 55 m do not actually exist. Thus, no use can be made of these standards as yet.

The standards within the meaning of § 13 para. 2 SeeAnlV and § 58 para. 2 WindSeeG also include the Convention for the Protection of the Marine Environment of the North-East Atlantic of 22.9.1992 (OSPAR Convention), which has its scope of application in the EEZ of the North Sea, and the Convention on the Protection of the Marine Environment of the Baltic Sea Area of 9.4.1992 (Helsinki Convention).

For the North Sea, Art. 2 section 2 OSPAR Decision 98/3 (OSPAR Commission 1998) on the Disposal of Decommissioned Offshore Installations prohibits the dumping and the complete or partial abandonment of decommissioned offshore installations within the maritime area. In accordance with

Art. 1 of the OSPAR Convention 1992 (OSPAR Commission 1992) however, offshore installations and activities are defined as follows:

> 'Offshore installation means any man-made structure, plant or vessel or parts thereof, whether floating or fixed to the seabed, placed within the maritime area for the purpose of offshore activities.'
>
> 'Offshore activities means activities carried out in the maritime area for the purposes of the exploration, appraisal or exploitation of liquid and gaseous hydrocarbons.'

The OSPAR Guidance on Environmental Consideration for Offshore Wind Farm Development (OSPAR Commission 2008) allows the competent authority to decide whether individual components of the wind farm should remain (e.g. parts of the pile in the seabed, scour protection layer (SPL)). The precondition is to ensure that there are no adverse effects on the environment, safety of navigation or other uses offshore.

BSH scope orders and public law contract

With regard to the scope of the obligation to decommissioning, legal certainty exists in individual cases if specific orders have been issued in the planning approval decision or in the permit. After the permit or the planning approval decision has become final, only the order on the scope of deconstruction made there is decisive. Even if the ordered decommissioning obligation is more far-reaching than that provided for by law, the official order must be observed.

The BSH regularly specifies decommissioning in the ancillary provisions of the permit or the planning approval decision. The obligation to decommission is stipulated in the ancillary clause 24. According to this, the offshore installations including all ancillary installations [...] are to be properly disposed of ashore after the permit or the planning decision expires. (BSH 2016). Earlier permits contain the wording that the installation must be dismantled and - demonstrably - properly disposed of ashore (BSH 2005). If these permits do not explicitly mention the ancillary facilities, a reference to them can be found in the more recent planning approvals. If the definition of the term "installation" is used as a basis, such a reference is not mandatory, as an installation includes these according to the WindSeeG and SeeAnlV (cf. the explanations on the scope of the term "installation" and the term "installation").

Subsidiary clause 24 also covers different prescribed cutting depths, which require an assessment and consideration of future sediment re-depositions. According to the geological and sedimentological conditions at the site, the BSH, as the competent technical authority, is responsible for the formulation of the ancillary provisions. The minimum cutting depth for decommissioning is always greater than 1m.

If, for example, the BSH has ordered that components of the foundation introduced into the seabed are to be removed below the upper edge of the seabed, the person obliged to do so must carry out the decommissioning to this extent (§ 58 Rn. 12Säcker 2017). This also applies if the reduced decommissioning is not associated with a risk of damage to the marine environment or if remaining parts of the installation provide a settlement and protection area for marine life. The reason for this is the validity of the planning approval decision or the permit (see above).

If the aim is to carry out decommissioning to a lesser extent than ordered, this is only possible if the BSH, on the basis of §§ 48, 49 of the Administrative Procedure Act (VwVfG), revokes an obligation to decommissioning ordered in a permit and reissues it in a modified (or reduced) form on the basis of § 13 para. 1 SeeAnlV. These are generally applicable principles of administrative law to which the BSH is also subject. § 48 VwVfG regulates the withdrawal of an unlawful administrative act; § 49 VwVfG regulates the revocation of a lawful administrative act after it has become final. Which norm is relevant depends on the BSH's opinion on the legal scope of the obligation to decommissioning in the individual case. The question here is whether the scope of the decommissioning is unlawful or lawful, taking into account the requirements of § 13 para. 1 SeeAnlV. It is solely at the discretion of the BSH whether the order imposing a decommissioning obligation should be revoked and whether a new order should then be issued in favour of the operator of the installation. The operator does not have a claim to this after the order has become final.

If the obligation to decommissioning is ordered in a planning approval decision, it must be taken into account in the event of a revocation by the BSH that §§ 48 and 49 VwVfG, according to their wording, limit the scope of application to administrative acts and do not extend to planning approval decisions. In more recent case law, however, the Federal Administrative Court applies §§ 48 and 49 VwVfG in principle also to planning approval decisions. (Bundesverwaltungsgericht (BVerwG), 3 A 8/15 vom 19.12.2017)

In the event that the BSH and the OWF operator agree on a decommissioning obligation that is more favourable to the operator, a public law contract on the scope of decommissioning may also be concluded between the two parties. According to § 54 S. 2 VwVfG, the BSH as a public authority may, instead of issuing an administrative act (order for decommissioning), also conclude a public-law contract with the party to whom it would otherwise address the administrative act. Such a contract may also include the cancellation of an order for decommissioning that has already been issued.

Responsibility for remaining plant components under the SeeAufG

In the event that plant components such as cables, SPL or FOU are not removed within the limits of § 13 SeeAnlV, § 58 WindSeeG or within the limits of decommissioning orders in the permit or planning approval, the owner remains responsible for the components. The SeeAufG regulates an extended responsibility for this condition, because the owner cannot even escape his responsibility by giving up his property.

In this respect, the property law provision in § 946 BGB, according to which a movable object becomes an essential part of a plot of land by being permanently connected to it, does not apply, so that the previous ownership of the movable object ceases to exist. The reason for this is that the EEZ is a no-man's land that cannot be appropriated under property law and cannot be entered in the land register (Leicht et al. 2020). Despite being anchored in the ground, the plants and thus also the plant components remain movable objects with special legal capacity for which a person, e.g., the plant operator, has a property right.

§ 3a (2) of the SeeAufG allows authorities to take hazard prevention measures if hazards emanate from the remaining parts. Since there are no more specific hazard prevention regulations, the SeeAufG applies. These measures can be directed against the holder of actual authority, the owner or another entitled party. Even if ownership is relinquished and the plant components are ownerless, the measures can be directed against the person who relinquished ownership of the object. There is no legal basis for a limitation period (Erbguth and Stollmann 2001).

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III System description

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3.1 System description

As part of the project, a system analysis is carried out to identify the systems and subsystems that will be considered in the research project *SeeOff.* The systems to be investigated are described by system parameters and system boundaries. The result of the system analysis thus forms the basis for the research project.

Within the framework of the research project, a distinction can be made between two systems:

1. The OWF and its components, for all of which dismantling and disposal must be considered as part of the decommissioning process.
2. The decommissioning process, i.e., the activities carried out during the decommissioning of an OWF. This decommissioning process can be divided into the dismantling processes offshore and shore side as well as recovery and disposal processes. A general description of the entire process can be found in chapter 3.2.

To define the **system boundary of** the considered structures and components, it is useful to distinguish between the areas of responsibility of the operator of an OWF and the transmission system operator. The operator is responsible for the wind turbine generator (WTG), the offshore substation (OSS), and the inter-array cabling (IAC). The transmission system operator is responsible for all structures and components connecting an OWF to the transmission grid (onshore). Thus, when an OWF connected to the transmission grid via high voltage direct current transmission is dismantled, in all likelihood the converter platform and the high voltage direct current export cable between the converter platform and the OSS will not automatically be dismantled too. However, it is assumed that the three-phase cable(s) (AC cables) between the OSS of the OWF and the converter platform will have to be dismantled. This also applies for those OWF that are directly connected to the transmission grid via one or more AC cables to an onshore substation. As a rule, the transmission system operator is responsible for dismantling the AC cables. Nevertheless, the dismantling of the AC export cable will be considered in the *SeeOff* research project. The transmission system operator’s converter platform, though, is located outside the system boundary. Hence, the dismantling of the following structures is considered:

- the offshore wind turbines (WTG),
- the foundation structures of the WTG (WTG-FOU),
- the offshore substation (OSS),
- the founding structure of the OSS,
- the scour protection layer (SPL),
- the inter-array cables (IAC) and
- the AC export cables.

3.1.1 Reference offshore wind farm and harbour

In order to analyse OWF decommissioning, a reference OWF and a reference harbour were defined within the research project *SeeOff*. OWF are very different in their design. The reference OWF has characteristics that can also be found in other OWF in the German Exclusive Economic Zone (EEZ). The systems and components of an OWF were analysed as part of a system analysis. The design of the reference OWF therefore reflects the characteristics found in the majority of German OWF in the EEZ as of 2019 (Start *SeeOff*) (section 1.1.2). It can be assumed that the first OWF to be decommissioned in the German EEZ will correspond to the design of the reference OWF.

The reference OWF is located in the German EEZ at a water depth of 20 to 30 m (mean water depth is 25 m) and is approx. 110 sm away from the reference harbour. The OWF consists of 80 turbines of the type Siemens SWT-3.6-120 Offshore on monopiles (MP). The SPL consists of an armour layer and a filter layer. The IAC are 33 kV cables with three different conductor cross-sections, the export cable is a 155 kV cable. The OSS consists of a topside with a jacket FOU.

3.1.1.1 Offshore wind turbine generator

The 80 WTG are Siemens SWT-3.6-120 offshore turbines. This is the most common WTG type in the 3-4 MW nominal power class, whose decommissioning is to be expected earlier than that of the 6-7 MW nominal power class (see Chapter 1.1). The rotor blades are made of glass-fibre reinforced plastic (GRP). For technical data of the reference WTG and the reference nacelle equipment see Table 16 and Table 17.

Table 16: Technical data of the reference offshore wind turbine generator

Component	Parameter	Value	Source
Hub	Hub height above LAT	88 m	Dan Tysk Offshore Wind GmbH 2014
	Weight	42.4 t	Lindvig 2010
Nacelle	Dimensions	4.1 x 4.2 x 20.0 m	Stiesdal and Madsen 2005; Siemens AG 2011
	Weight	125 t	Lindvig 2010
Tower	Height	66 m	Own assumptions of the SeeOff project partners
	Weight	180 t	Lindvig 2010
	Diameter, tower base	5 m	Own assumptions of the SeeOff project partners
	Diameter, tower top	3 m	Own assumptions of the SeeOff project partners
	Wall thickness	28 mm	Calculated from mean diameter

Component	Parameter	Value	Source
Rotor blade	Length	58.5 m	Stiesdal and Madsen 2005; Siemens AG 2011
	Weight	17.2 t	Lindvig 2010s

Table 17: Technical data of the reference nacelle equipment

Component	Parameter	Value	Source
Gearbox	Dimensions	4.3 x 3.3 x 2.5 m	Own assumptions of the *SeeOff project partners*
	Weight	33.0 t	Own assumptions of the *SeeOff project partners*
Generator	Dimensions	2.7 x 1.8 x 2.3 m	Own assumptions of the *SeeOff project partners*
	Weight	10 t	Own assumptions of the *SeeOff project partners*
Transformer	Dimensions	2.4 x 1.3 x 3.3 m	Own assumptions of the *SeeOff project partners*
	Weight	7 t	Own assumptions of the *SeeOff project partners*

3.1.1.2 Transition Piece

The WTG are flanged on the transition piece (TP) and connected to the monopile (MP) via a grouted connection.

Table 18: Technical data of the reference transition piece

Component	Parameter	Value	Source
Transition Piece	Total height	27 m	Per Aarsleff A/S 2018
	Diameter, bottom	6.3 m	Per Aarsleff A/S 2018
	Diameter, top	5.0 m	Per Aarsleff A/S 2018
	Wall thickness	74 mm	Per Aarsleff A/S 2018
	Weight	286 t	Per Aarsleff A/S 2018
Grout	Volume	11.8 m^3	Own assumptions of the *SeeOff project partners*
	Mass	28.3 t	Own assumptions of the *SeeOff project partners*

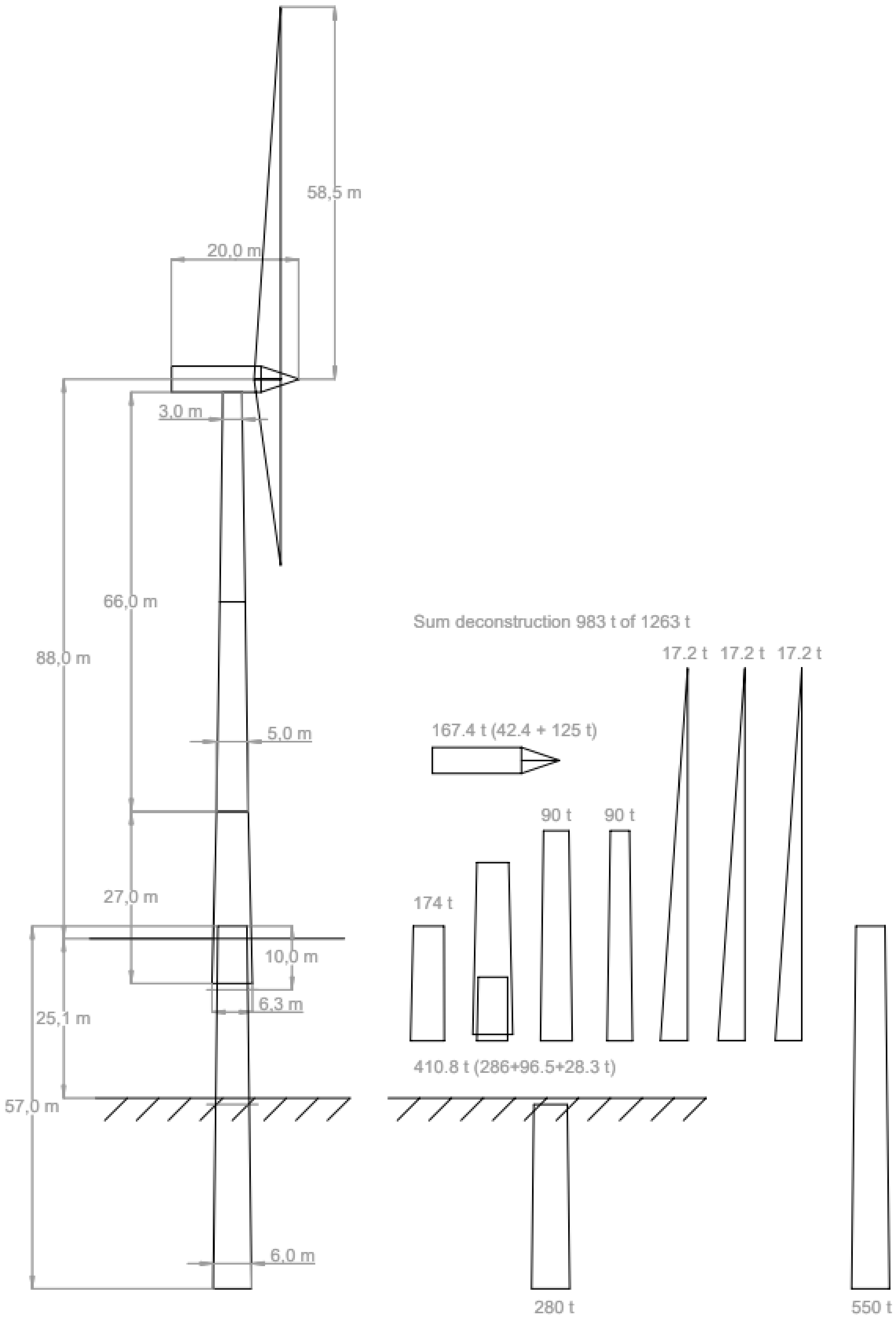

Figure 35: Dimensions and masses of the reference wind turbine generator and foundation

3.1.1.3 Monopile

MP are the most frequently found foundations in the German EEZ (see chapter 1.1.2.2). The MP of the reference OWF have an assumed mean length of 57 m, of which 30 m are in the seabed and 9 m in the TP.

Table 19: Technical data of the reference monopile

Component	Parameter	Value	Source
Monopile	Medium length	57 m	Provided by Vattenfall Europe Windkraft GmbH
	Diameter	6 m	Per Aarsleff A/S 2018
	Medium weight	550 t	Provided by Vattenfall Europe Windkraft GmbH
	Average weight per metre	9.65 m	Own calculations
	Wall thicknesses	80-126 mm	Provided by Vattenfall Europe Windkraft GmbH

Within the research project *SeeOff*, different scopes of decommissioning are investigated. With regard to the MP, the following options are considered:

- Cutting the MP 1 m below the seabed (state of the art)
- Cutting the MP 3 m above the seabed
- Complete removal of the MP

The MP is cut 1 m below the TP in each case. This results in the dimensional assumptions shown in Table 20.

Table 20: Dimensions of the monopile (MP) for different decommissioning options

Decommissioning option	MP in TP		MP only		In seabed	
Cutting the MP 1 m below the seabed	10 m	96.5 t	18 m	173.5 t	29 m	280 t
Cutting the MP 3 m above the seabed	10 m	96.5 t	14 m	135 t	33 m	318.5 t
Complete removal of the MP	10 m	96.5 t	57 m	435.5 t	0 m	0 t

3.1.1.4 Scour protection layer

At all WTG locations there is a SPL consisting of a filter layer and a top layer. The filter layer was installed on the seabed before the MP were erected. Both the filter layer and the top layer consist of granite stones of different sizes (see Table 21).

Table 21: Technical data of the reference scour protection layer per location

Component	Parameter	Value	Source
Filter layer	Height	0.75 m	Own assumptions based on (Esteban et al. 2019b)
	Filter bed diameter	40 m	Own assumptions based on (Esteban et al. 2019b)
	Volume	721 m^3	Own calculation
	Particle diameter	0.05-0.2 m	Own assumptions based on (Esteban et al. 2019b)
	Weight	1000 t	Own calculation
Top layer	Height	1.4 m	Own assumptions based on (Esteban et al. 2019b)
	Filter bed diameter	18 m	Own assumptions based on (Esteban et al. 2019b)
	Volume	356 m^3	Own calculation
	Particle diameter	0.4-0.5 m	Own assumptions based on (Esteban et al. 2019b)
	Weight	462 t	Own calculation

3.1.1.5 Inter-array cables

All 80 WTG are connected to the OSS via 33 kV IAC. In total, the reference OWF has an IAC network length of 105 km of 33 kV cables with different conductor cross-sections (120 mm^2: 40 km length, 300 mm^2: 30 km length, 500 mm^2: 35 km length). The cable route is divided into 86 cables (each cable section has a length of 1.22 km on average). The cables are covered with 0.6 m sediment and are equipped with a cable protection system at the cable ends (Table 22). The technical data of the IAC is shown in Figure 36.

Table 22: Technical data of the reference inter array cables

Cable cross-section	Parameter	Value	Source
120 mm^2	Length	40 km	Provided by Vattenfall Europe Windkraft GmbH
	Weight	16.2 t/km	(Nexans 2008)
	Weight, total	648 t	Own calculation
300 mm^2	Length	30 km	Provided by Vattenfall Europe Windkraft GmbH
	Weight	24.1 t/km	(Nexans 2008)
	Weight, total	723 t	Own calculation
500 mm^2	Length	35 km	Provided by Vattenfall Europe Windkraft GmbH
	Weight	33.4 t/km	(Nexans 2008)
	Weight, total	1 169 t	Own calculation

3.1.1.6 Export cable

The OSS is connected to the converter via two 155 kV export cables. The two offshore platforms are 10 km apart. The cables are covered with 0.6 to 1 m sediment.

Table 23: Technical data of the reference export cable

Cable cross-section	Parameter	Value	Source
400 mm^2	Length	2 x 10 km	Provided by Tennet Offshore GmbH
	Weight	70 t/km	Provided by Tennet Offshore GmbH
	Weight, total	1 400 t	Own calculation

3.1.1.7 Offshore Substation

On the OSS the voltage is transformed from 33 kV to 155 kV. The OSS topside is founded on a jacket structure that is anchored in the seabed with four driven piles.

Table 24: Technical data of the reference offshore substation

Component	Parameter	Value	Source
OSS Topside	Length	42 m	Redaktion Schiff&Hafen 2013
	Wide	36 m	Redaktion Schiff&Hafen 2013
	Height	30 m	Redaktion Schiff&Hafen 2013
	Weight, total	3 000 t	Own calculation
OSS Jacket	Length	30 m	Provided by Vattenfall Europe Windkraft GmbH
	Wide	30 m	Provided by Vattenfall Europe Windkraft GmbH
	Height	45 m	Provided by Vattenfall Europe Windkraft GmbH
	Weight	1 100 t	Naaijkens n.d.
Framed piles	Amount	4	Naaijkens n.d.
	Length	90 m	Own calculation based on Naaijkens n.d.
	Weight, total	800 t	Naaijkens n.d.

Table 25: Technical data of the reference OSS equipment

Component	Parameter	Value	Source
155 kv transformer	Dimensions	5 x 5 x 10 m	Own assumptions of the SeeOff project partners
	Weight per component	150 t	Own assumptions of the SeeOff project partners
	Number	2	Own assumptions of the SeeOff project partners
155 kV GIS	Dimensions	6 x 10 x 5 m	Own assumptions of the SeeOff project partners
	Weight per component	30 t	Own assumptions of the SeeOff project partners

Component	Parameter	Value	Source
	Number	2	Own assumptions of the SeeOff project partners
155 kV choke coil	Dimensions	3.5 x 5 x 5 m	Own assumptions of the SeeOff project partners
	Weight per component	75	Own assumptions of the SeeOff project partners
	Number	2	Own assumptions of the SeeOff project partners
Petersen coil	Dimensions	1.8 x 2 x 5 m	Own assumptions of the SeeOff project partners
	Weight per component	15 t	Own assumptions of the SeeOff project partners
	Number	2	Own assumptions of the SeeOff project partners
33 kV neutral point former	Dimensions	3 x 3 x 4 m	Own assumptions of the SeeOff project partners
	Weight per component	17 t	Own assumptions of the SeeOff project partners
	Number	2	Own assumptions of the SeeOff project partners
33 kV reactor	Dimensions	2 x 2.5 x 3.2 m	Own assumptions of the SeeOff project partners
	Weight per component	10 t	Own assumptions of the SeeOff project partners
	Number	2	Own assumptions of the SeeOff project partners
33 kV GIS	Dimensions	1 x 1 x 2.5 m	Own assumptions of the SeeOff project partners
	Weight per component	1 t	Own assumptions of the SeeOff project partners
	Number	30	Own assumptions of the SeeOff project partners
Power transformer	Dimensions	1.5 x 2.5 x 2.5 m	Own assumptions of the SeeOff project partners
	Weight per component	10 t	Own assumptions of the SeeOff project partners
	Number	2	Own assumptions of the SeeOff project partners

3.1.1.8 Base harbour

The reference decommissioning base harbour is a harbour on the German mainland. The harbour has an area of 6 ha and has a roll on/roll off quay (100 m long) and a lift on/lift off quay (150 m x 400 m depth).

It is assumed that all components, with the exception of the SPL, are transported to the reference harbour and comminuted there. The SPL, on the other hand, is transported directly to another area with a corresponding quay edge, where it is stored until further use. This area is also located about 110 sm away from the reference OWF.

3.1.2 Mass balance of the reference offshore wind farm

There are 226 366 t of material installed in the entire OWF. Stones (SPL, 51.67 M-%) and steel (41.67 M-%) together account for 93.34 M-% of the mass fraction of the total OWF; GRP 1.92 M-%, cast iron 1.88 M-%, copper 1.04 M-% and construction waste 1.00 M-%. All other materials are represented with less than 1 M-% each (Table 26, Figure 37). Other studies often show higher mass fractions of steel (Tota-Maharaj and McMahon 2020; Topham et al. 2019b), however, no SPL was taken into account in these studies.

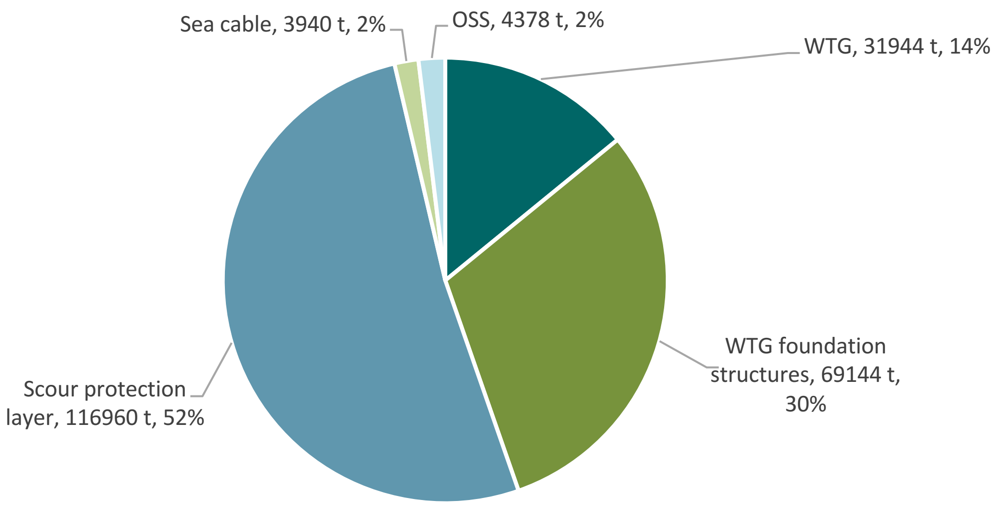

Figure 37: Mass and percentage shares of wind turbine generator (WTG), WTG foundation structure, scour protection layer, sea cables and offshore substation (OSS) of the reference OWF.

Table 26: Mass balance of the materials of the reference OWF

Material flow	WTG		WTG-FOU		SPL		Sea cables		OSS (Topside and FOU)		total	
	in t	in M-%	in t	in M-%	in t	in M-%	in t	in M-%	in t	in M-%	in t	in M-%
Steel	21 913	9.68	66 724	29.48	0	0.00	1 980	0.87	3 705	1.64	94 322	41.67
Stainless steel	72	0.03	0	0.00	0	0.00	0	0.00	1	0.00	73	0.03
Cast iron	4 247	1.88	0	0.00	0	0.00	0	0.00	5	0.00	4 252	1.88
Aluminium	180	0.08	0	0.00	0	0.00	0	0.00	2	0.00	182	0.08
Copper	747	0.33	136	0.06	0	0.00	1 166	0.52	296	0.13	2 346	1.04
GRP	4 343	1.92	0	0.00	0	0.00	0	0.00	0	0.00	4 343	1.92
Stones	0	0.00	0	0.00	116 960	51.67	0	0.00	0	0.00	116 960	51.67
Building rubble (Grout)	0	0.00	2 264	1.00	0	0.00	0	0.00	0	0.00	2 264	1.00
div polymers/ plastics	246	0.11	16	0.01	0	0.00	0	0.00	125	0.06	387	0.17
F-Gases	0	0.00	0	0.00	0	0.00	0	0.00	0.48	0.00	0	0.00
SF_6	0	0.00	0	0.00	0	0.00	0	0.00	3	0.00	3	0.00
Household waste	16	0.01	0	0.00	0	0.00	0	0.00	0	0.00	16	0.01
Bulky waste	0	0.00	0	0.00	0	0.00	0	0.00	150	0.07	150	0.07
Lubricants	52	0.02	0	0.00	0	0.00	0	0.00	64	0.03	116	0.05
Diesel	0	0.00	0	0.00	0	0.00	0	0.00	18	0.01	18	0.01
Lead (batteries)	8	0.00	0	0.00	0	0.00	414	0.18	6	0.00	428	0.19
Other	119	0.05	4	0.00	0	0.00	380	0.17	3	0.00	506	0.22
total	31 944	14.11	69 144	30.55	116 960	51.67	3 940	1.74	4 378	1.93	226 366	1.00

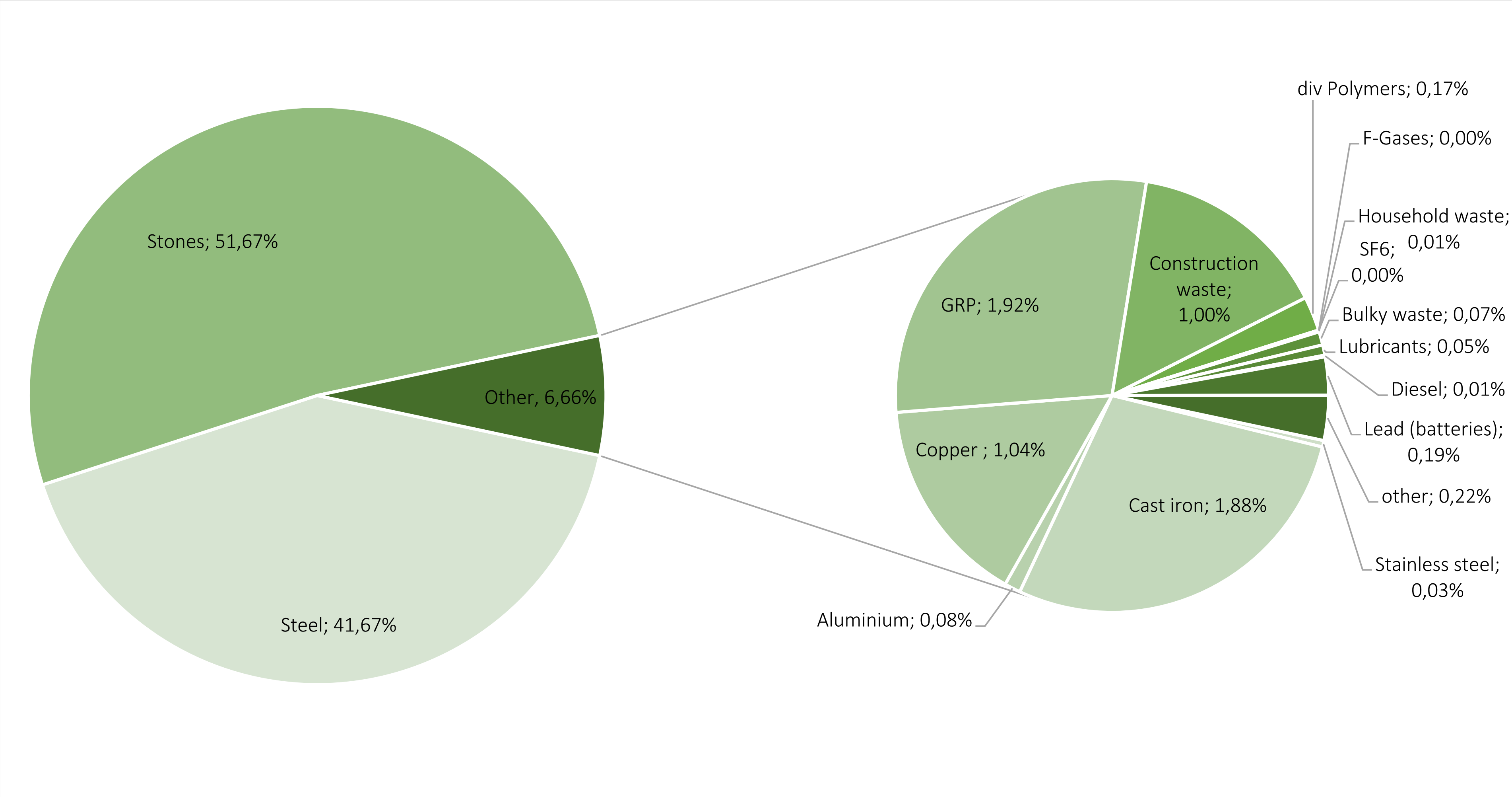

Figure 38: Percentage distribution of materials of the reference offshore wind farm (total mass: 226 366 t)

In the above illustration, the WTG includes the rotor-nacelle assembly and the tower. The rotor blades are mainly made of GRP, the hub of cast iron. Steel accounts for the largest mass share of the nacelle, but cast iron and copper are also present in larger quantities. The tower and FOU (TP and MP) are almost exclusively made of steel, with approximately M-10 % of the TP weight attributable to the grout connection, i.e., construction waste. The largest mass fraction of the WTG is accounted for by the SPL or stones (Table 27, Figure 38).

Table 27: Mass balance of the reference wind turbine generator

	Mass in t			
	Rotor blades	Hub	Nacelle	Tower
Steel	1	0.0	94.7	178.2
Stainless steel	0.0	0.0	0.9	0.0
Cast iron	0.0	41.4	11.7	0.0
Aluminium	0.0	0.0	0.5	1.8
Copper	0.0	0.0	9.4	0.0
GRP	50.0	1.0	3.0	0.0
Stones	0.0	0.0	0.0	0.0
Building rubble (Grout)	0.0	0.0	0.0	0.0
div polymers/plastics	0.0	0.0	3.1	0.0
SF_6	0.0	0.0	0.0	0.0
Household waste	0.0	0.0	0.2	0.0
Lubricants	0.0	0.0	0.7	0.0
Lead (-batteries)	0.0	0.0	0.1	0.0
Other	0.3	0.0	1.2	0.0
total	51.6	42.4	125.3	180.0

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IV Integration of sustainability, stakeholder and process approaches for sustainable offshore wind farm decommissioning

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ABSTRACT

At the end of their operational life offshore wind farms need to be decommissioned. Up to date only few offshore wind farms were decommissioned, so there is a lack of experience and knowledge and decommissioning processes are largely unknown. Also, relevant stakeholders that might interfere with the decommissioning project are poorly investigated. As source of renewable energy, offshore wind farm decommissioning should be sustainable. This paper outlines a practical concept of integrating the three approaches for a sustainable decommissioning of offshore wind farms. It comprises a stakeholder approach, where relevant stakeholders are identified and analysed, a sustainability approach, in which objectives for sustainable offshore wind farm decommissioning are defined, and a process approach, including the selection, documentation and parametrization of decommissioning processes. The theoretical concept of the integration of the three approaches is outlined first. Thereafter the concept is applied on a case study of offshore wind farm decommissioning.

1. Introduction

Throughout Europe there were offshore wind farms (OWF) with 22,072 MW installed capacity and 5047 turbines in operation by the end of 2019 [1]. Leading countries in the offshore wind industry are the United Kingdom (9945 MW and 2225 turbines), Germany (7445 MW and 1469 turbines), Denmark (1703 MW and 559 turbines), Belgium (1556 MW and 318 turbines) and the Netherlands (1118 MW and 365 turbines) [1]. In order to reach Germany's goal to cover 80% of the gross electricity consumption by renewable energies until 2050, the installed capacity of OWFs in the German Economic Exclusive Zone has to be increased up to 20,000 MW until 2030 [2].

At the end of their operational life (usually 20–25 years), OWFs need to be decommissioned. Up to date, only five OWFs were decommissioned worldwide: the Swedish offshore wind farms *Yttre Stengrund* (decommissioned in 2016) and *Utgrunden* (decommissioned in 2018), the Dutch OWF *Lely* (decommissioned in 2016), the Danish wind farm *Vindeby* (decommissioned in 2017) and UK OWF *Blyth* (decommissioned in 2019) [3,4,4,5] [5]. These wind farms were rather small in turbine number (2–11 turbines) and turbine power (450–2000 kW) and were located near shore (0.8–7.3 km distance to shore) in shallow waters (4–15 m water depth) [4–6]. Therefore, experiences cannot be transferred to decommissioning of larger OWFs further offshore in deeper waters. Decommissioning projects are rather unique, as OWFs differ in number and size of turbines as well as in types of foundation structures and are located at varying water depths and distances to shore. Therefore, standard decommissioning procedures are not feasible, but a general concept is required that allows for the development and assessment of an individual decommissioning strategy for each OWF under consideration. In Germany, the approval authority sets minimum requirements with the 'Standard Design – Minimum requirements concerning the constructive design of offshore structures within the Exclusive Economic Zone (EEZ) [7]' and the 'Standard – Investigation of the Impacts of Offshore Wind Turbines on the Marine Environment (StUK4)' [8]. Both of the standards, however, focus primarily on the construction and operational phase. Further, in Germany with the approval for the construction of the OWF, the approval holder is obliged to decommission the OWF at the end of its operational life. The detailed planning of the decommissioning, however, depends on the current state

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Abbreviations

ProOpt	Decommissioning process option
GHG	Greenhouse gas
OWF	Offshore wind farm
ProCr	Criteria for the selection and exclusion of processes
SDG	Sustainable Development Goals
StakeCat	stakeholder category
StakeGr	Stakeholder group
SustAsp	Sustainability aspect
SustAttr	Sustainability attribute
SustCat	Sustainability category
SustDeCr	Sustainability decision criteria
SustObj	Sustainability objective

of the art and is largely left to the permit holder.

Decommissioning is the last phase of the life cycle of an OWF. It involves the dismantling of the entire physical structure which includes the wind energy turbines, the offshore substations, the foundation structures and inner array cables. Deinstallation and transport vessels are required for the dismantling and shipment. Selection of vessel type is highly dependent on dismantling techniques. A variety of dismantling techniques for offshore structures is either already available, e.g. diamond saws and water jetting, or under development such as complete removal by generating overpressure within the pile [9]. Onshore wind turbines taken out of service are often re-erected in other countries, e.g. in eastern Europe is a well-established market for reuse of complete wind turbines or single components [10]. For OWFs a second life is rather unlikely. However, certain components might be reused as spare parts and hence need to be handled with appropriate care. At the harbour site OWF components are further dismantled. Here components are fragmented to appropriate sizes and potentially separated to readily recyclable materials. Finally, the components and materials are distributed to the corresponding recycling facilities.

Up to date, there is a lack of detailed knowledge on how to decommission OWFs and on the corresponding processes. Techniques and procedures for offshore dismantling as well as their feasibility, particularly of foundation structures, are not sufficiently elaborated. Detailed concepts for offshore logistics, waste management and reduction of costs are lacking as well.

It can be expected that many stakeholders will be involved in OWF decommissioning, e.g., approval holders, authorities, service companies or consulting offices. These may follow different, possibly conflicting objectives. For example, operators might be interested in low decommissioning costs, safety-at-work might be of importance to service companies, environmental authorities might place most relevance on environmental protection, whereas the entire offshore wind industry probably supports techniques and procedures of decommissioning that come along with high public acceptance. The identification of relevant stakeholders and their relevance at an early stage is of high relevance to develop appropriate strategies on stakeholder involvement. Till today no in-depth surveys of stakeholders of OWF decommissioning are available.

So far, the majority of analysis and assessments of decommissioning of offshore structures focus on individual aspects. Some publications consider financial aspect [11,12] or the potential of using decommissioned offshore installations as artificial reefs [13,14]. A few publications propose the joint consideration of economic, environmental and social aspects of decommissioning [15–17]. However, they do not consider the entire decommissioning process, but focus on special aspects like partial vs. complete decommissioning. Being renewable energy plants, OWF decommissioning should be sustainable over the entire decommissioning processes.

In order to overcome these shortcomings, a practical concept was developed that integrates three approaches (procedure based on [18–20]) (see Fig. 2):

(1) *Sustainability approach*: Categories that specify relevant topics of sustainability of OWF decommissioning are identified. Decision criteria consisting of objectives and attributes, that measure the achievement of the objectives, are defined for each category.
(2) *Stakeholder approach*: Stakeholders involved in OWF decommissioning are identified and grouped according to their expertise. Based on an analysis of their characteristics, stakeholders are categorised according to their relevance to the project. Strategies on how to involve stakeholder in OWF decommissioning can be deduced from this approach.
(3) *Process approach*: Decommissioning processes that have to be analysed in detail are selected first. Documented processes are parametrized as this allows for the assessment of performance regarding the sustainability attributes.

The integrated consideration of all three approaches allows to answer the following questions: 1) Which are the relevant stakeholders in sustainable OWF decommissioning and how should they be involved? 2) What are the objectives of sustainable OWF decommissioning? 3) How to identify relevant options of decommissioning OWF and how can these be assessed regarding their sustainability?

The practical concept of how to incorporate the three approaches is outlined in chapter 2. In chapter 3 the concept is applied to a case study of OWF decommissioning.

2. Practical concept of integrating the three approaches

2.1. Sustainability approach

The sustainability approach focuses on the consideration of sustainability aspects in strategic decision-making processes. In 2015 the United Nations published the Agenda 2030 for sustainable development with a total of 17 Sustainable Development Goals (SDG) for the economic, environmental and societal sectors [21]. In order to realise sustainable offshore wind farm (OWF) decommissioning, these SDGs should be considered.

As sustainability is a wide field, it is feasible to first establish a hierarchical structure of sustainability topics relevant to the project, here the decommissioning of OWFs. On the first level sustainability

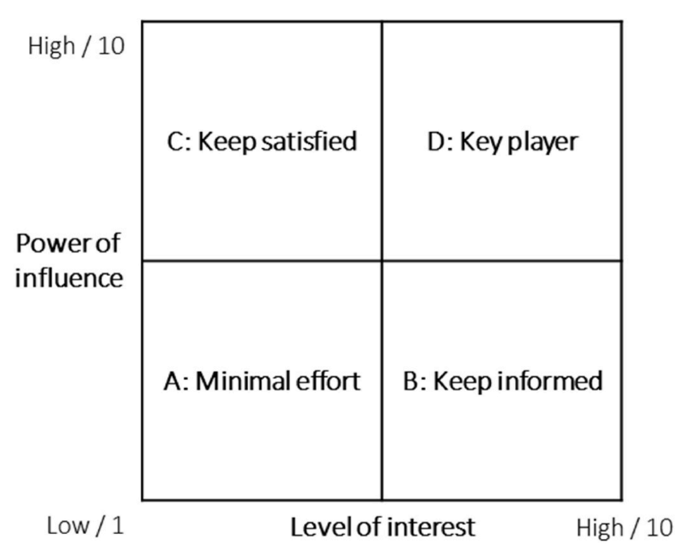

Fig. 1. Stakeholder categories (A–D) according to their level of interest versus power of influence [25].

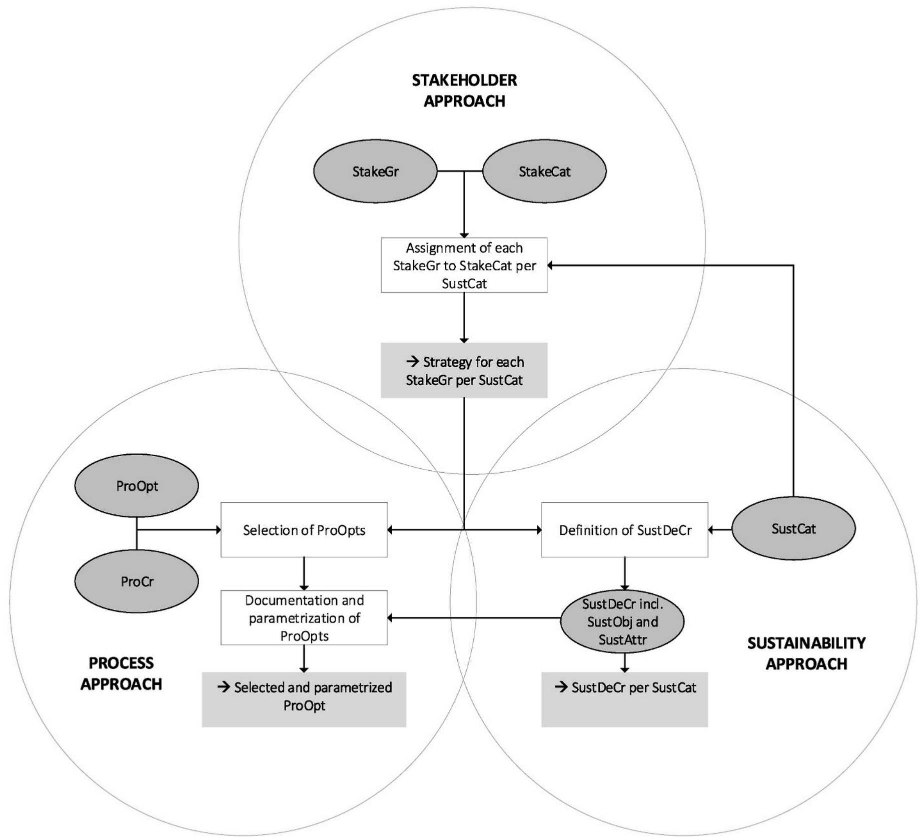

Fig. 2. Practical concept for the integration of the stakeholder, sustainability and process approaches (StakeGr = Stakeholder group, StakeCat = Stakeholder category, SustCat = Sustainability category, SustDeCr = Sustainability decision criteria, SustObj = Sustainability objective, SustAttr = Sustainability Attribute, ProCr selection/exclusion criteria for process selection, ProOpt = Decommissioning process options).

categories (SustCat) are defined based on the three pillars of sustainability: *economic*, *environmental* and *social*. As these SustCats are still rather general, sustainability aspects (SustAsp) that specify relevant issues of the SustCat are identified. For example, *greenhouse gas (GHG) emissions* and *resource efficiency* are relevant SustAsps of the SustCat *environment.* Thereafter, sustainability decision criteria (SustDeCr) are defined for each SustAsp. SustDeCr consist of a sustainability objective (SustObj) and attribute (SustAttr) that measures the achievement of the SustObj [22]. According to Ref. [22], objectives are 'statements about a desired state or outcome of a system under consideration and indicate potentials for improvement'. Attributes measure the achievement of the objectives and are required to quantify the performance of the process options. While the SustAsp already help to narrow down the SustCats but still remain on a higher level, SustDeCr are very case-specific and need to be defined for each OWF decommissioning project in close association with relevant stakeholders [22].

Sustainability profiles enable a structured and detailed documentation. They should at least contain information on the SustCats, SustAsp and SustDeCr, i.e. consisting of SustObj and SustAttr, and the information on whether the SustAttr is to be minimised or maximised. Explanations and contribution to SDGs can be supplemented.

2.2. Stakeholder approach

Identification and consideration of influential stakeholders is essential for successful decommissioning project realisation. The most relevant stakeholders are decision makers. For OWF decommissioning these are (1) approval holders, usually the operators or shareholders, who decide on a specific decommissioning plan and (2) the approval authority that has to evaluate and approve the decommissioning plan. Guidelines and instructions of the approval authority would influence decommissioning plans prepared by the approval holder significantly. However, up-to-date there are only few requirements and specifications for OWF decommissioning; for example the German Standard Design [7] and StUK4 [8] or the UK Guidance notes for industry [23].

Relevant stakeholders are not only decision makers, but also other parties that may interfere with such a project, either by supporting or opposing it [20]. A well-known example is the decommissioning of the oil platform *Brent Spar* by Shell UK in the 1990th. Initially, the company intended to sink the platform. However, after a public indignation, initiated by a Greenpeace campaign, and occupation of the platform, Shell UK was forced to refrain from their plans. Currently, decommissioning programmes for the platforms *Brent alpha*, *Brent Bravo* and *Brent Charlie* are developed, incorporating stakeholders and addressing safety-related, environmental, impacts on communities and economic aspects [24]. An assessment of relevant stakeholders is thus of crucial importance for projects of public interest.

Stakeholder assessment should follow these steps: 1. identification and grouping of stakeholders, 2. analysis of stakeholder characteristics and assignment of stakeholder categories and 3. development of strategies for dealing with stakeholders (procedure modified after [20]).

First, stakeholders are identified and grouped according to their expertise, e.g. *authorities* or *operators*, (StakeGr) [20]. Secondly, StakeGrs are characterised and classified in four stakeholder categories (StakeCat): A: *Minimal effort*, B: *Keep informed*, C: *Keep satisfied* and D: *Key players* [25]. Power and interest are two key characteristics of stakeholders. Interest is defined as 'the interest each stakeholder has in imposing its expectations on the organisation's purposes and choice of strategies' and power is defined as 'the power each stakeholder has to influence a strategy' [25]. Both characteristics can be expressed on a numerical scale, e.g. from 1 (low power of influence or level of interest) to 10 (high power of influence or level of interest). When power and interest are contrasted against each other, the power of influence and the level of interest enables the classification of stakeholders in the four StakeCats (see Fig. 1) [25].

It is very likely that the level of interest and the power of influence varies between SustCats for different StakeGr, e.g. for an *environmental authority* both characteristics are likely to be high in the *envionmental* SustCat but rather low in the *social* SustCat. Therefore, the StakeGr should be assigned to StakeCats for each of the three SustCat.

Depending on the StakeCat, strategies for handling stakeholders throughout a project can be deduced. *Key players* are characterized by a high level of interest and high power of influence. These stakeholders should thus be involved when defining SustCats and SustDeCr as well as when selecting decommissioning processes (see chapter 2.3). Stakeholders of StakeCat C: *Keep satisfied* (e.g. *authorities*) have a high level of power but only low level of interest, at least as long as their requirements are fulfilled. Stakeholders of StakeCat B: *Keep informed*, on the other side, possess a high level of interest, but only low power of influence. They should be monitored closely, as they might become *Key players*, if they gain power (e.g. by forming a citizen movement). Stakeholder of StakeCat A: *Minimal effort* are usually not very interested in the project and have only little power to interfere with it, so they require the least amount of attention. The assignment of stakeholder to the StakeCats is not fixed. If stakeholders gain or lose power or interest they might move from one StakeCat to another. It is hence advised to recheck the affiliation of the stakeholders throughout the project [25].

2.3. Process approach

Once StakeGrs are assigned to StakeCats for each SustCat and SustDeCr are defined, OWF decommissioning processes need to be investigated. If there is little to no experiences, such as in OWF decommissioning, these processes are assessed for the first time. To establish a sufficient knowledge base, literature research and consultation of experts of the same or related fields is essential. Information gathered should include state of the art OWF and related decommissioning concepts and techniques e.g. from offshore oil and gas, but also current scientific investigations and regulatory requirements. Also, experiences from construction or operation and maintenance phase should be considered.

To gain an overview, a general high-level structure of the decommissioning processes should be established first. Each OWF decommissioning project can be structured in three main processes: the dismantling of OWF components offshore, the dismantling and preparation of OWF components onshore as well as the waste processing. On a more detailed level, the decommissioning processes cannot be standardized. This is partly related to the few experiences and to the individual nature of OWFs, as decommissioning is expected to be project-specific. Therefore, options on how to realise decommissioning (ProOpt) should be collected. ProOpts are different courses of actions, including execution or non-execution of activities (e.g. remove scour protection or leave scour protection in place) as well as different types of execution (e.g. use of different dismantling techniques or utilization of vessel fleet). Selection of ProOpts influence concurrent, upstream and/or downstream processes. In order to allow for substitution and comparison, the ProOpts need to be documented standardized. As the analysis of decommissioning processes is very time-consuming, analysing all conceivable ProOpt is not expedient. Therefore, meaningful ProOpt need to be selected. Exclusion and selection criteria (ProCr) support the choice of appropriate ProOpts. Exclusion criteria define minimum requirements that need to be fulfilled in order to take a process in consideration. Selection criteria define processes that are of relevance for the achievement of objectives.

The selected ProOpt need to be analysed in depth. Therefore, they need to be documented first. Depth and manner of documentation is always target-oriented. Business Process Model and Notation (BPMN) Standard 2.0 is a possible option to document processes in a structured way. It is a semi-formal, standardised notation for the modelling of business processes [26]. Also, processes documented according to this standard allow for process parametrization. Parametrization is required to measure the performance of the processes regarding the SustAttr.

3. Putting the concept to practice: case study on sustainable decommissioning of offshore wind farms in German waters

The practical concept for the integration of the three approaches introduced in this paper is developed and applied within the research project 'SeeOff – Strategieentwicklung zum effizienten Rückbau von Offshore-Windparks[1]' ('Development of sustainable decommissioning strategies for offshore wind farms'). The consortium of project partners consists of research institutions, representatives of interest of the offshore wind industry, experts of OWF service, onshore wind farm decommissioning and recycling as well as associated partners being OWF operators and an electricity transmission system operator. The project is supported by a diverse advisory board and many other interested organisations of the OWF industry and related fields (incl. for example the approval authority, OWF and onshore wind farm service companies, logistic companies, consultants for and representatives of economic, environmental, health and safety-related and acceptance-related companies). The participation of this great variety of stakeholders enabled the application of the concept. An online survey was carried out as part of the stakeholder approach. Within the sustainability approach, objectives for sustainable OWF decommissioning were discussed with stakeholders of the OWF industry at a workshop. Decommissioning processes were described, discussed and documented in collaboration with the corresponding experts.

3.1. Sustainability in German offshore wind farm decommissioning

In order to assess sustainability of OWF decommissioning, the *economic*, *environmental* and *social* SustCats were subdivided into more specific SustAsp. A total of seven SustDeCr for sustainable OWF decommissioning were defined. SustCats, SustAsps and SustDeCr were transferred into a hierarchy (Fig. 3) and sustainability profiles for OWF decommissioning were developed (Table 2). The profiles were discussed and evaluated with about 60 experts from different disciples of the OWF industry at a workshop.

Within the *SeeOff* project, a total of seven SustDeCr were defined that are of special relevance to OWF decommissioning; one for the economic, two for the social and four for environmental SustCat. The calculation of actual decommissioning costs, for example, is associated with a high uncertainty [11,31]. Consequently, a SustDeCr was defined for economic efficiency of OWF decommissioning. As decommissioning of today's OWFs is not realized up to date and processes are largely unknown, safety-at-work and hazards towards employees is a topic of great relevance. In order to prevent public resistance during decommissioning, the aspect of public acceptance was selected as well. It might appear somewhat out of balance to only define a single decision criterion for economics, but two for the social categories and four for environment. However, the impacts of offshore wind farms on the environment are still not completely understood. In Germany, monitoring programmes usually run until the fifth year of operation and are only prolonged on demand [8]. Hence, the current legal monitoring programme does not allow for estimating long-term influences of OWF on the marine environment. Still there are numerous publications that point out (possible) effects of OWF and other man-made structures on benthic and fish communities [28,30,32,33]. Thus, effects of OWF decommissioning on biodiversity and commercial species are of great

[1] *SeeOff* is a three-year research project (01.11.2018–31.10.2021) funded by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag (grant number: 0324322, www.seeeoff.de).

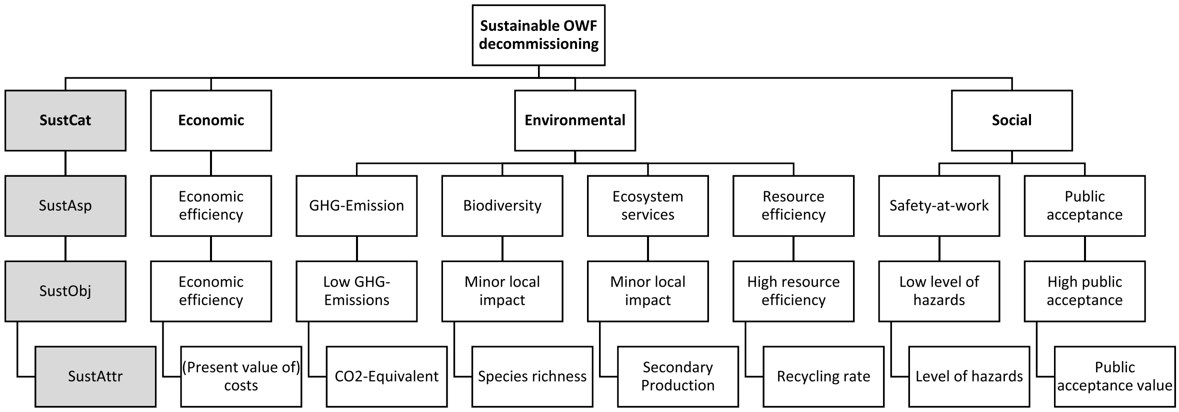

Fig. 3. Hierarchy of SustCats, SustAsps, SustObj and SustAttr for sustainable OWF decommissioning (see Table 1 for acronyms). For definitions and further explanations see Table 2.

Table 1
List of acronyms and corresponding terms and definition of the sustainability, stakeholder and process approaches.

Acronym	Term	Definition
Sustainability approach		
SustCat	Sustainability category	Reflect important topics of sustainability (economic, environmental and social topics)
SustAsp	Sustainability aspects	Specify relevant aspects of SustCats
SustDeCr	Sustainability decision criterion	Each SustDeCr consists of a SustObj and a SustAttr
SustObj	Sustainability objective	Desired state/outcome of OWP decommissioning with regards to sustainability
SustAttr	Sustainability attribute	Measure the achievement of the SustObj
Stakeholder approach		
StakeGr	Stakeholder groups	Groups of stakeholders according to their expertise (e.g. *operators* or *authorities*)
StakeCat	Stakeholder category	Characterisation of stakeholders regarding to their power of influence and level of interest (*Key players, Keep satisfied, Keep informed* and *minimal effort*)
Process approach		
ProOpt	Process Option	Process options on how to realise OWF decommissioning
ProCr	Selection/ Exclusion Criterion	Selection/ Exclusion criterion for the selection of ProOpts

interest, but not yet fully understood. As part of the ongoing public discussion on climate change in relation to offshore wind being a renewable energy source, emission of GHG as well as resource efficiency along the entire OWF life cycle are major issues of concern. Hence, the types and compilation of SustDeCr for sustainable OWF decommissioning is supposed to not only reflect direct objectives of certain stakeholder but also to address issues of broader interests.

3.2. *Stakeholders of sustainable offshore wind farm decommissioning within the case study*

Within the research project *SeeOff* stakeholders of OWF decommissioning were characterised according to their level of interest and power of influence within the *economic*, *environmental* and *social* SustCats. Therefore, a three-week online stakeholder survey (using SurveyMonkey by the Company SurveyMonkey Inc. San Mateo, California, USA www.surveymoneky.com) was conducted in May and June 2019. The survey addressed stakeholders that are or will be involved directly or indirectly in decommissioning of OWFs or that are generally interested in the topic. 81 responses were of suitable quality to be processed for in-depth analysis.

In order to identify relevant stakeholders and group them appropriately, the participants of the stakeholder survey were asked to assign themselves to StakeGr (e.g. *authority*) and to specify their group (e.g. *approval authority*). Table 3 gives an overview on the types and numbers of stakeholders that participated in the survey. *Operators of OWFs* (n=13) and *electricity transmission system operators* (n=4) responded most frequently, followed by *authorities* (n=10), *consulting companies* (n=10) and *research institutes/universities* (n=9). Response was low in StakeGrs *manufacturer* (n=1), *waste management companies* (n=2), from the *finance* sector (n=3) and *suppliers* (n=3). These stakeholder groups are included in the analysis, but will not be discussed in detail. No stakeholder of the category *certification/ inspection bodies* participated, so this category is excluded from analysis and discussion.

In order to assign StakeGr to StakeCats for the *economic*, *environmental* and *social* SustCats, the survey participants were characterised according their power of influence and level of interest. To assess the power of influence the survey participants were asked to rate their level of influence on *economic*, *environmental* and *social* aspects (*social* aspects were broken down to *safety-related* and *acceptance-related* aspects) of OWF decommissioning on a scale of 1 (no influence) to 10 (great influence). The level of interest was assessed by rating the level of affectedness by *economic*, *environmental*, *safety-related* and *acceptance-related* aspects of OWF decommissioning on a scale of 1 (not affected) to 10 (very affected). In all four SustCats the majority of the stakeholders were assigned either to the StakeCat A: *Minimal effort* ($\bar{x}_{freqA}$: 0.35–0.49) or D: *Key Players* ($\bar{x}_{freqD}$: 0.32–0.49) (Table 4). Only few survey participants were assigned to StakeCat B: *Keep informed* ($\bar{x}_{freqB}$: 0.06–0.11) or category C: *Keep satisfied* ($\bar{x}_{freqC}$: 0.04–0.10).

In order to gain information on the StakeCats in each SustCat, the SustCats were investigated in detail individually. As an example, the assessment of the *environmental* SustCat is outlined (Table 5). Within this SustCat, the majority of the surveyed members from StakeGrs *planning and service companies* ($freq_D = 0.86$, $n_D = 6$) and *operators* ($freq_D = 0.76$, $n_D = 13$) were assigned to StakeCat D: *Key players*. The two survey participants of *operators* that were assigned to StakeCat A: *Minimal effort*, were employees of OWF operators with expertise in project certification. Survey participants of the StakeGr *authorities*, *consulting companies* as well as *dismantling and repowering companies* were assigned to StakeCat A: *Minimal effort* and StakeCat D: *Key players* in similar shares (Table 5). To explain this effect, more detailed information on each StakeGr is required. E.g. *environmental authorities* and *environmental planning offices* are assigned to StakeCat D: *Key players*, whereas *economic authorities* or *auditing companies* are more likely to be assigned to StakeCat A: *Minimal effort*.

For the other SustCats the following StakeGr were categorised to be

Table 2
Sustainability profiles for OWF decommissioning (see Table 1 for acronyms).

SustCat		Economic	Social	Social
SustAsp		Economic efficiency	Safety-at-work	Public acceptance
SustDeCr	**SustObj**	From a business point of view, OWF decommissioning is economically efficient	OWF decommissioning is associated with a low level of hazards	OWF decommissioning is associated with high public acceptance
	SustAttr	(Present value of) costs	Level of hazard	Public acceptance value
	Minimisation/ Maximisation of SustAttr	Minimisation	Minimisation	Maximisation
Explanations		The defined output (decommissioned OWF) should be realized with lowest input. The economic efficiency assesses the resource input with the associated costs.	In the construction and demolition industries, several hazards often simultaneously overlap at different intensities. Therefore, hazard assessments are required by law, in which all hazard factors are recorded and the risk is assessed in order to take possible preventative measures. The attribute level of hazard combines amount, duration and consequences of probable hazards.	Even though renewable energy sources are highly promoted, wind farms are often discussed controversially, particularly due to their possible impacts on the environment and high costs. High public acceptance of OWF decommissioning will promote overall acceptance of this industry.
Contribution to SDGs		SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all [21] SDG 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all [21]	SDG 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all [21]	

SustCat		Environmental	Environmental	Environmental	Environmental
SustAsp		Greenhouse gas (GHG) emissions	Biodiversity	Ecosystem services	Resource efficiency
SustDeCr	**SustObj**	OWF decommissioning is associated with low GHG emissions	OWF decommissioning has minor impact on local biodiversity	OWF decommissioning has minor impct on local biomass of commercially fished species	OWF decommissioning is associated with high resource efficiency
	SustAttr	CO_2-Equivalents	Species richness	Secondary production	Recycling rate
	Minimisation/ Maximisation of SustAttr	Minimisation	Maximisation	Maximisation	Maximisation
Explanations		Renewable energies are an important part in the combat of climate change. OWF should not only contribute by providing energy, but also by having low GHG emissions over the entire life cycle.	Foundation structures of OWF are hard substrate habitats. Research studies have shown an influence of foundations structures on biodiversity of benthic species [27–29].	Sustainable use of marine commercial species is of great global relevance. Research suggests that OWFs, in particular the foundation structures, might act as a refugium for commercially relevant fish and benthos species [27,28,30].	Recycling is a key aspect to increase resource efficiency. Therefore, in order to benefit resource efficiency a high recycling rate should be targeted when decommissioning OWFs.
Contribution to SDGs		SDG 13: Take urgent action to combat climate change and its impacts [21]	SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development [21]	SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development [21]	SDG 12: Ensure sustainable consumption and production patterns [21]

Table 3
Number of survey participants per stakeholder group (StakeGr).

StakeGr	Number of survey participants
Operator	17
Authority	10
Consulting company	10
Research institute/ university	9
Association/ representative	7
Logistic company	7
Planning and service company	7
Dismantling/ Repowering company	5
Finances	3
Supplier	3
Waste management company	2
Manufacturer	1
Certification/ Inspection body	0
∑	81

Key Players:

- *Economic*: *operators* ($freq_D = 0.71$, $n_D = 12$), *logistic companies* ($freq_D = 0.71$, $n_D = 5$) and *planning and service companies* ($freq_D = 0.71$, $n_D = 5$)
- *Safety-at-work*: *operators* ($freq_D = 0.88$, $n_D = 15$), *planning and service companies* ($freq_D = 0.71$, $n_D = 5$) and *logistic companies* ($freq_D = 0.71$, $n_D = 5$)
- *Acceptance*: *operators* ($freq_D = 0.59$, $n_D = 10$) and *planning and service companies* ($freq_D = 0.57$, $n_D = 4$)

Table 4
Mean relative frequency ($\bar{x}_{freq}$) and absolute number (n) of stakeholders (per StakeCat (A – D)) per SustCat (see Table 1 for acronyms).

SustCats	StakeCat							
	A *Minimal effort*		B *Keep informed*		C *Keep satisfied*		D *Key players*	
	$\bar{x}_{freq}$	n	$\bar{x}_{freq}$	n	$\bar{x}_{freq}$	n	$\bar{x}_{freq}$	n
Environmental	0.35	28	0.11	9	0.06	5	0.48	39
Economic	0.39	32	0.10	8	0.05	4	0.46	37
Social: Safety-at-work	0.41	33	0.06	5	0.04	3	0.49	40
Social: Acceptance	0.49	40	0.09	7	0.10	8	0.32	26

The assessment showed that the stakeholders are most often assigned to the StakeCat A: *Minimal effort* and D: *Key players*. More detailed

Table 5
Relative frequency (freq.) and number of respondents (n) per StakeGr and StakeCat A to D in the SustCat: *Environmental* (see Table 1 for acronyms).

SustCat: *Environmental*	StakeCat							
	A *Minimal effort*		B *Keep informed*		C *Keep satisfied*		D *Key players*	
StakeGr	freq.	n	freq.	n	freq.	n	freq.	n
Authority	0.50	5	0.00	0	0.00	0	0.50	5
Association/ representative	0.43	3	0.29	2	0.14	1	0.14	1
Consulting company	0.50	5	0.10	1	0.00	0	0.40	4
Dismantling and Repowering company	0.40	2	0.00	0	0.00	0	0.60	3
Finances	0.67	2	0.33	1	0.00	0	0.00	0
Logistic company	0.29	2	0.43	3	0.14	1	0.14	1
Manufacturer	0.00	0	0.00	0	0.00	0	1.00	1
Operator	0.12	2	0.06	1	0.06	1	0.76	13
Planning and service company	0.14	1	0.00	0	0.00	0	0.86	6
Research institute/ university	0.56	5	0.00	0	0.22	2	0.22	2
Supplier	0.33	1	0.00	0	0.00	0	0.67	2
Waste management company	0.00	0	0.50	1	0.00	0	0.50	1

information on the StakeGr explains this opposing allocation even within individual StakeGr. For example, within the StakeGr *authorities* the *environmental authorities* probably possess more power and are more interested in environmental aspects of decommissioning than *economic authorities*. This clear differentiation might also reflect a defined allocation of competences and responsibilities, which might be beneficial for the overall planning and organisation of decommissioning approval process.

In-depth knowledge of the assignment of stakeholders to a certain StakeCat for each SustCat enables the development of appropriate strategies for dealing with the individual stakeholders. *Key players* should be involved in the entire decommissioning project, starting with the planning phase. Accordingly, *operators*, *planning and service companies* as well as respective *authorities* and *consulting companies* should participate at developing strategies and objectives within the category environment, while it should mainly be *operators* and *planning and service companies* that should be consulted on safety-related issues. However, the focus should not only be laid upon *Key Players*. Stakeholders of the StakeCat B: *Keep informed* are usually very interested, but possess only little power of influence. If these stakeholders gain power (e.g. by forming citizens' initiative), they can become *Key Players* that might interfere with the decommissioning project, possibly with significant impact, e.g. causing delays or even the termination of the project [25]. Stakeholders of StakeCat C: *Keep satisfied* are usually organisations which needs should be fulfilled. Usually, a typical stakeholder of this category is the *approval authority* [25]. The results of this study, however, show that *authorities* are almost exclusively assigned either to category A: *Minimal effort* or category D: *Key Players*. The assignment to category D: *Key Players* might reflect the relevance of the topic due to the lack of knowledge and high corresponding uncertainty in regulatory framework as well as feasibility and impacts of OWF decommissioning. Also, *authorities* from different areas of specialisation participated in the survey, e.g. OWF approval, nature conservation or economics. Specialists usually have a high interest and might possess a high level of power in their area of expertise, but only little interest and power in other fields. This can explain the high proportion of *authorities* in the StakeCats A: *Minimal effort* and D: *Key Players*. As stakeholders of the StakeCat A: *Minimal effort* usually possess only a low level of interest and power of influence, they demand no or only little attention [25]. Nonetheless, these players should at least be monitored throughout the project. For example, the results show that within the category *safety-at-work* the StakeGr *research institutes/universities* is assigned to StakeCat A: *Minimal effort*. Depending on developments within the area of research, the level of interest might increase and the project could profit from their expertise.

3.3. Decommissioning processes for German offshore wind farms

Based on extensive literature research and knowledge on prior OWF project phases, decommissioning processes were established in cooperation with *SeeOff* project partners and other experts of the offshore and onshore wind industry, related industries such as offshore oil and gas, and other involved organisations like the approval authority. Fig. 4 gives an overview of decommissioning of the OWF components to secondary materials or secondary fuels and measures of SustAttr. The overall decommissioning process comprises the dismantling of OWF components (OWF turbine incl. foundation, inner array cables, offshore substation incl. foundation) offshore, their dismantling and preparation onshore and waste processing.

ProOpts for the individual processes were collected. For the offshore and onshore dismantling and preparation processes, a component perspective is feasible where each OWF components is considered. For example, offshore wind turbines are broken down into the dismantling of rotor blades (which could be lifted individually or as a rotor star), of nacelle and hub and of the tower (which could be lifted in one or in individual segments) [34]. Onshore the components are disassembled, prepared and separated, so that for waste processing processes, a waste fraction-perspective is more suitable. Wastes deriving from a nacelle include for example scrape metals, glass reinforced plastics, electrical and electronical waste, cables and lubricants [10].

For a closer look at the selection of ProOpts, let's consider different scopes of decommissioning. Currently, the German Offshore Wind Energy Act (Windenergie-auf-See-Gesetz) and the incidental provisions to the approval determine that OWFs need to be decommissioned completely. So we assume, that the foundation structures are cut 1 m below sea floor and that inner array cables and scour protection are removed (Decommissioning scenario 1, Table 6). However, if partial decommissioning is to be considered, different ProOpts can be specified. Within the research project SeeOff, it is considered that inner array cables might be left in situ, as the standard incidental provisions of the approval of OWF refer to the OSPAR Decision 98/3 [35] wherein parts located below the surface of the sea bed are not included in the definition of disused offshore installation. Foundation structures and scour protection were found to provide habitat for hard substrate dwelling species [27,28,30,33]. Therefore, leaving those structures or parts of them in situ is also taken in account. Table 6 summarizes the ProOpts for different scopes of turbine foundation dismantling considered; the foundation structure could be cut 1 m below or 3 m above seabed, the scour protection and the inner array cables could either be removed or left. ProOpts can be combined to decommissioning scenarios, e.g. foundation structure is cut 1 m below sea bed, inner array cables are removed, but scour protection is left in place (decommissioning scenario 2).

Table 6 lists a total of five decommissioning scenarios, considering the following aspects. Having to remove scour protection, but leaving inner array cables and cutting foundation structures 3 m above sea floor, is very unlikely. Also, leaving scour protection in place is assumed to have little influence on the subsequent use of the OWF area, e.g. if a new OWF is to be build. Hence, in all, but the first decommissioning scenarios, scour protection is left in place. Remaining foundation structures are supposed to always need to be taken into consideration when planning new OWF, irrespective of whether they were cut 1 m below or 3 m above sea floor. Removal or leaving in place of the inner array cables, on the other hand, will strongly affect the layout and erection of new OWF. Combining these ProOpts and considering the complete decommissioning, results in five possible combinations and decommissioning scenarios for different scope of decommissioning of wind turbine foundation structure (Table 6).

Beyond the scope of decommissioning, there are many other ProOpts that can be taken into consideration. Offshore vessels are major cost

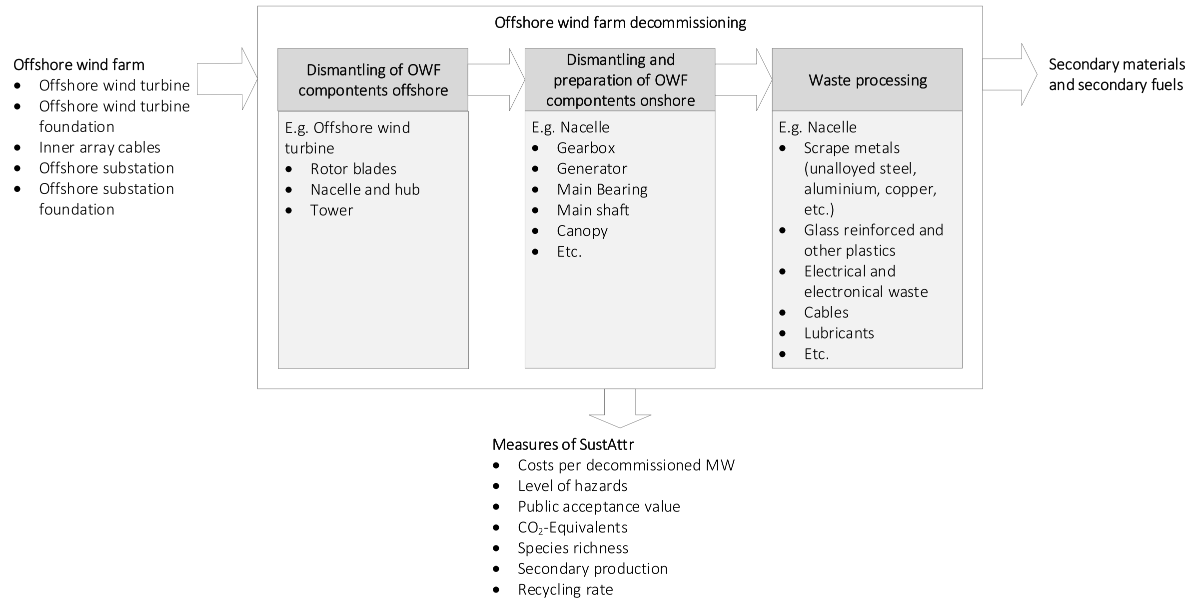

Fig. 4. OWF decommissioning process including input (components of an OWF) and output (Secondary material and secondary fuels as well as measures of sustainability attributes (SustAttr)).

Table 6
Possible options (ProOpts) and scenarios of different scopes of OWF decommissioning.

ProOpts						Decommissioning scenarios
Foundation		Scour protection		Inner array cable		
cut 1 m below sea bed	cut 3 m above sea bed	leave	remove	leave	remove	
x			x		x	1
x		x			x	2
	x	x			x	3
x		x		x		4
	x	x		x		5

Table 7
Criteria for the exclusion and selection (ProCr) of process options (ProOpts).

	Category	ProCr	Explanation for selection and exclusion of process options
Exclusion criteria	General	Availability of data and information	• Data and information are not sufficiently available are to be excluded
Selection criteria	Environment	GHG-emissions	• Different amounts of GHGs are emitted
		Recycling	• Variation in amount of recycled material • Influence on material flow
		Fish and benthos	• Influence on the features of conservation interest fish and benthos
	Economic	Economic efficiency	• Associated to relevant costs • Variation in resource inputs (type and duration)
	Social	Accidents	• Number of accidents (after [39])
		Hazards	• Variation in degree of potential of hazards • Long-lasting exposure to hazard • Hazards resulting in severe consequences • Multiple, simultaneous hazards
		Public acceptance	• Different levels of public acceptance

drivers, therefore different vessel types and composition of the fleet could be taken into consideration [34]. Also, where and how the OWF components are fed to the different waste management options can have major impacts on sustainability. The onshore logistic sector for example contributes to GHG emissions [36]. Selected options for waste processing and material recovery, influence costs and revenues of materials like copper or aluminium, the emission of GHG and, of course, resource efficiency [10,37,38]. Combining all possible ProOpts would result in a multitude of decommissioning scenarios, which might not be expedient. Therefore, ProOpts need to be selected and combined carefully.

ProCr were defined for the selection of ProOpts; a single general exclusion criterion and seven selection criteria (Table 7). The general exclusion criterion focuses on the availability of data and information, as this is the foundation for the assessment of the process options. Requirements that need to be fulfilled, in order to consider ProOpt, were compiled within the research project in a separate catalogue. The selection criteria were grouped according to the SustCats *environment*, *economics* and *social*.

Once ProOpts were selected, they were documented in such a manner and to such a level required to measure the SustAttr. Fig. 5 depicts a simplified operational process of the offshore dismantling of wind turbines and shows that CO_2-Equivalents should be investigated for each activity of the process. After the process is initiated, a vessel travels to the OWF, where the rotor blades are dismantled first, followed by the dismantling of nacelle and hub as well as of the tower. Afterwards the vessel travels to the next wind turbine for dismantling. This is repeated until either the vessel capacity is reached or all wind turbines are removed. Then the vessel travels back to the harbour where the wind turbine components are unloaded. If not all wind turbines are dismantled, the vessel travels back to the wind farm and continue dismantling.

An exemplary parametrization to calculate CO_2-Equivalents of the fuel-consuming activities, like transportation with vessels, rail or trucks or operation of equipment like cranes, is depicted in Fig. 6. With the fuel consumption and fuel type, to derive conversion factors of GHGs, as well as the duration and number of repetitions of the activity, emissions of carbon dioxide, nitrous oxide and methane can be calculated. Based thereon CO_2-Equivalents can be estimated.

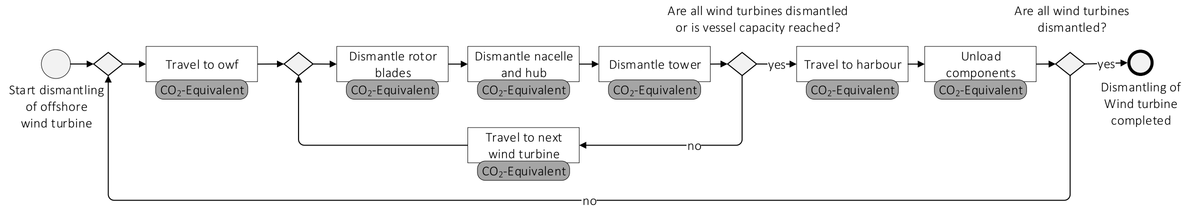

Fig. 5. Operational process of the offshore dismantling of wind turbines using BMPN 2.0 notation: squared boxes (= activities) illustrate work that is actually performed, circles (=events) stand for something that happens and have a cause or an impact on the flow (each process has at least a start and an d event), at rhombuses (=gateways) process flows are branched and/or joined and can either go in parallel or follow just a single path [40]. Grey-shaded boxes with round corner hold the sustainability attribute.

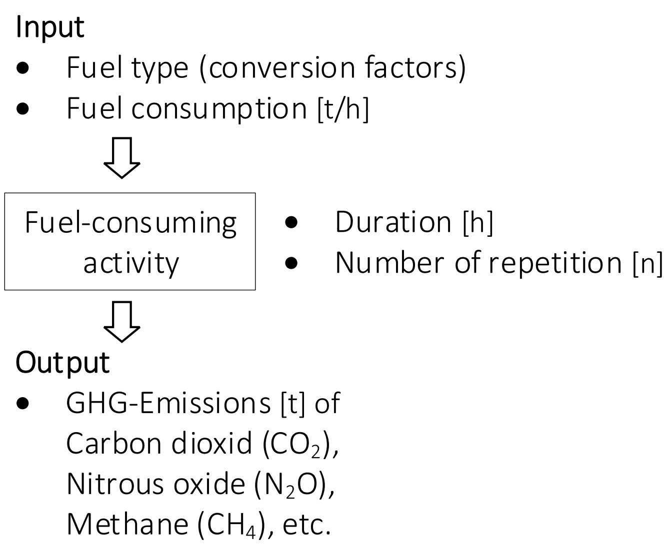

Fig. 6. Exemplary parametrization of a fuel-consuming activity.

The availability of data and information might influence process parametrization. For example, when assessing CO_2-Equivalents of processes involving a jack-up vessel it can be assumed that fuel consumption of vessels is affected by the activity performed (e.g. traveling, jacking or lifting) and whether it is traveling with or without turbines components. Whether or not information on fuel consumption exists on that level of detail or whether it is made available to the process analysist has impacts on process parametrization.

Parametrization to calculate CO_2-Equivalents of fuel-consuming activities is very straight forward and only minor adaptions are required for the estimation of CO_2-Equivalents of energy-consuming activities. For other SustAttr like level of hazards, parametrization is much more complex, as detailed information on the activity itself as well as associated hazards is required.

Further, relations between up- and downstream processes should be taken into consideration. Some decision made upstream of the process, e.g. whether the OWF is dismantled completely or only partially, can influence downstream processes, e.g. the quantities of materials for recycling. Therefore, it is important to consider the entire decommissioning process.

4. Wider concept application and future research

The incorporation of the three approaches allows for the identification on how to involve relevant stakeholder groups (StakeGr) on certain sustainability topics (SustCat) in offshore wind farm (OWF) decommissioning. Also, it enables the definition of relevant sustainability objectives (SustObj) and how to measure processes regarding their achievements of these objectives (SustAttr). Further, meaningful process options on how to decommission an OWF (ProOpts) can be selected based on exclusion and selection criteria (ProCr). These ProOpts are parametrized to allow for the assessment regarding the SustAttr.

In order to identify options for decommissioning with the best performance regarding sustainability (SustDeCr) further research is required. Multi-criteria decision analysis (MCDA) appears to be an appropriate tool. A variety of specific MCDA methods and options to group them is available [18,19]. They all allow for the comparison of different alternatives (in this case the ProOpts) under consideration of various interests (in this case the SustDeCrs) and also support group decision-making (in this case the consideration of the StakeGrs). The selection of the appropriate MCDA method is always case-specific and depends for example on whether there is a finite or infinite number of alternatives available or whether it is targeted to identify the optimal solution for a problem or the best of the available alternatives [18].

Within the research project *SeeOff* first results were collected. As every OWF is unique, a case-specific application of the concept integrating the three approaches is strongly advised. Even though SustCats should be the same, SustObj can be expected to vary. Also, the StakeGrs and the assignment to the StakeCats should be rechecked. Due to the individual nature of the OWFs it is very likely that decommissioning processes on a detailed level and ProOpts are very different. Future experience in OWF decommissioning will contribute to refining the selection of relevant stakeholders, objectives and processes. Last but not least it needs to be considered that decommissioning of most OWFs still lies a couple of years in the future. Until then regulations might have changed, state of the art of decommissioning techniques and procedures will have developed and other issues might have moved to the focus of public attention.

5. Conclusion

This practical concept on how to integrate stakeholder, sustainability and process approaches was developed and applied to OWF decommissioning for the first time. Relevant stakeholders were identified, objectives and attributes for sustainable OWF decommissioning were defined and processes on how to decommission OWFs were structured and described. Particularly, if knowledge and experiences as well as legal frameworks are scarce or lacking, this integrated approach allows to consider the interests of all stakeholders involved and thereby counteracting possible resistance towards or delays of the decommissioning project. By incorporating the sustainability approach, the focus is not only laid on realising OWF decommissioning with high economic efficiency, but also environmentally-friendly, safe and publicly accepted.

When the regulatory framework is associated with uncertainties, the practical concept introduced in this paper is particularly useful. As in the case of OWF decommissioning, currently the approval holder is obliged to prepare a decommissioning plan without a sound basis of requirements and specifications. Hence, considering all relevant stakeholders as well as economic, environmental and social aspects when designing OWF decommissioning, should increase the acceptance by the approval authorities.

This approach can be applied on any project that involves multiple stakeholders possibly with different interests and targets a sustainable realisation. Particularly renewable energy projects can profit from this concept, as these should always be sustainable over the entire life cycle. Hence, the consideration of economic, environmental and social aspects is of major importance. Also, stakeholder involvement is of great relevance, as some renewable energy sources are discussed very controversially, e.g. the impacts of onshore wind farms on local residents and wild life. The practical concept can be of special support, if renewable energy projects reach a project phase with little experiences or knowledge, as in the case of decommissioning of OWF, or for example, if they are to be newly introduced to countries or areas. By exploring the processes together with the relevant stakeholders with regards to those sustainability aspects of importance in the context of the respective project, possible resistances can be reduced. The integration of the stakeholder, sustainability and process approaches can consequently support a successful realisation of those projects.

Nonetheless, further investigations can improve the practical concept outlined above. To verify the concept and the results of the case study, it should be applied on actual OWF decommissioning. Also, to prove transferability, the concept should be used in the context of other fields of renewable energies like onshore wind farms or bioenergy projects. Further research is required, regarding the utilization of appropriate MCDA methods. Methods for the identification of the most suitable decommissioning options for the decommissioning of OWF are of special importance.

Credit author statement

Vanessa Spielmann: Conceptualization, Methodology, Research, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. Thomas Brey: Validation, Writing – original draft, Supervision. Jennifer Dannheim: Validation, Writing – original draft, Writing – review & editing. Jesper Vajhøj: Research: Decommissioning processes, Writing – original draft. Mandy Ebojie: Research: Safety-at-work objectives, attributes and selection criteria, Writing – original draft. Johanna Klein: Research: Economic efficiency objectives, attributes and selection criteria, Writing – original draft. Silke Eckardt: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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V Develop the scientific basis for assessing the conservation of benthic habitats beyond the exploitation phase of marine renewable energy installations (ToR d)

S Birchenough, A Boon, U Braekman, T Brey, R Brzana, J Buyse, A Capet, D Carey, P Causon, J W P Coolen, J Dannheim, J.-C. Dauvin, P Davies, I De Mesel, S Degraer, A Gill, V Guida, M Harrald, Z Hutchison, U Janas, P Kloss, R Krone, C Labrune, M Laverre, N Lefaible, N Mavraki, I Muxika, F O`Beirn, J-P Pezy, A Raoux, M Rasser, E Sheehan, V Spielmann, E Trager, J Vanaverbeke, P Vinagre and T Wilding

WORKING GROUP ON MARINE BENTHAL AND RENEWABLE ENERGY DEVELOPMENT (WGMBRED). ICES Scientific Reports, 2021, 3 (63), 8-11

4 Develop the scientific basis for assessing the conservation of benthic habitats beyond the exploitation phase of marine renewable energy installations (ToR d)

4.1 Introduction

In 2015, Lindeboom *et al.* concluded that the overriding lesson from more than a decade of monitoring of environmental impacts of European offshore wind farms (OWFs) is that OWFs do change the local environment. These changes span all ecosystem components, and some can be regarded as (potentially) undesirable, e.g. avoidance and collisions of birds and some (potentially) desired, e.g. increased biodiversity and enhanced local fish populations (e.g. Wilhelmsson *et al.*, 2010; Lindeboom *et al.*, 2011; Bergström *et al.*, 2014). To enable distinguishing between desired and undesired effects a fundamental understanding of the effects is needed. Contrary to basic monitoring, targeted monitoring and research as adopted by the Belgian WinMon.BE and the Dutch WOZEP programs, directly contribute to such understanding by investigating the underlying ecological processes (or cause-effect relationships) behind (a selected set of) observed impacts (Hutchison *et al.*, 2020).

Much is already known about the cause-effect relationship at the basis of OWF effects, as reviewed for the benthos by Dannheim *et al.* (2020). They identified the cause-effect relationships between different activities related to OWF construction and operation, and three impact types of societal relevance, i.e. impacts on biodiversity, food resources and biogeochemistry, comprising abiotic and biotic ecosystem features and their interactions. The science-base for each of these cause-effect relationships is elaborated in their supplementary material.

While Dannheim *et al.* (2020) covered the impacts of activities related to OWF construction and operation, they did not cover the impacts of activities related to decommissioning. However, OWFs are temporary constructions most often allowed to occupy marine space only for a limited period of time after which they are to be decommissioned (Birchenough and Degraer, 2020). In the Northeast Atlantic, the present-day commitment under the OSPAR Convention is to fully remove the OWFs when they are decommissioned. However, derogations from the general principle of complete removal may apply.

The expected ecological effects of removal practices comprise, e.g. the removal of the established artificial hard substrate community, elevated turbidity, elevated underwater sound and/or an increased risk of ship collisions and pollution, which are considered to be detrimental to marine ecosystems (Birchenough and Degraer, 2020). On the other hand, the removal of OWFs will allow restoration of the natural habitat, reversing the artificial reef effect, but at the same time also the protection by the *de facto* fisheries exclusion. A new challenge hence is the planning of decommissioning scenarios for OWFs. This will have to be judged by whether it is e.g. environmentally beneficial to apply derogation (e.g. “rigs-to-reefs”), or to partially or completely remove these structures. To date, there are substantial gaps in the knowledge base needed to support science-based decisions on this topic. These knowledge gaps include how the (partial) removal of the artificial reef and fisheries exclusion effect may further affect the marine ecosystem.

4.2 Objective

Our study targeted the assessment of what effects of OWFs will change during and after decommissioning under different scenarios of decommissioning, taking account of the new baseline.

The following definitions were adopted for the sake of this initiative:

- Decommissioning: a formal process to remove something from an active status (Wikipedia) (for our purpose "to remove" is widened to from leaving the structure in place over redevelopment to full removal)
- Change: no longer take place, strengthen/weaken, or even newly show up
- Baseline: the ecosystem as it has developed with the OWFs in place

Note that to tackle what effects of OWFs will change during and after decommissioning, as is targeted in this study, does not equal to tackle what the direct effects of decommissioning are. In practice, we analysed for a selection of decommissioning scenarios:

- What cause-effect relationships (CERs) are likely to disappear?
- What CERs are likely to change in effect size (in space and time)?
- What CERs are likely to newly appear?

4.3 Research strategy

First, we identified realistic decommissioning scenarios, after which we revisited the CERs as described in Dannheim *et al.* (2020). Decommissioning scenarios were based on an interview with Vanessa Spielmann (Hohschule Bremen) engaged in a German project investigating decommissioning scenarios for OWFs, and a discussion within WGMBRED. Revisiting the Dannheim *et al.* (2020) CERs comprised (1) the qualitative identification of obsolete and missing activities and CERs during decommissioning and after decommissioning, and (2) a quantitative (i.e. effect size and direction) assessment of change of CERs. During this exercise we have only tested the applicability of revisiting the CERs (i.e. proof-of-concept) without executing a comprehensive analysis of change which will be done in a next step. Proof-of-concept exercises were executed for the partial decommissioning scenario and two impact types, i.e. impacts on biodiversity and impacts on food resources. The comparison made is from the pre-decommissioning baseline to the post-decommissioning status 5 years on. Therefore, the deconstruction activities were not under consideration at this time. Additionally, we only considered the effects in relation to a single turbine, not the whole wind farm and only wind farm related effects, not those relating to the use of the space after decommissioning.

4.4 Results

Decommissioning scenarios

Four decommissioning scenarios were considered representing realistic future decommissioning strategies: (1) do nothing, (2) partial removal (leave the lowest 5 m in place, incl. scour protection layer and cable), (3) full removal (turbine cut below the seafloor, scour protection layer and cables removed), and (4) redevelopment (construct new wind farm at same lease area, with full removal of old wind turbines). Only the first three scenarios were further considered in this study because the fourth scenario will ultimately lead to the same CERs as in Dannheim *et al.* (2020) (Figure 1).

The removal of monopiles will likely happen making use of jack-up vessels similar to the ones used for piling activities. Removal will take place after the monopiles are cut loose about 1 m below the sediment surface either by water jet cutting (high pressure water jet mixed with sand; most likely scenario) or diamond sawing from the inside of the monopiles or the use of targeted (fine-scale) explosives. To cut the monopiles, sediments need to be flushed from around the turbine to get access to ~1 m below seabed with consequent impacts on suspended matter concentrations in water column and on the surrounding scour protection layer (cf. flushing will most likely affect the full extent of the scour protection layer). No information on how to remove gravity-based foundations is available as yet, but it is evident that prior to removal, the sand added to achieve "gravity" will have to be taken out and deposited somewhere prior to removal of the structure, increasing suspended matter concentrations in the water column. The removal of the scour protection layer (not applicable for jacket foundations) will be executed making use of caterpillars (see e.g. Goliath Van Oord) which will impact suspended matter concentrations in the water column. The removal of cables will be done by "reversed" cable laying vessels, pulling cables out instead of digging in after the end of the cable has been freed from the sediment. Some dredging may be or is needed to free up the end of the cable, including a possible removal of the scour protection layer. Deviation from this methodology is expected at locations of cable crossings. Shipping during (partial) removal works are likely going to be similar to what may be expected during construction works.

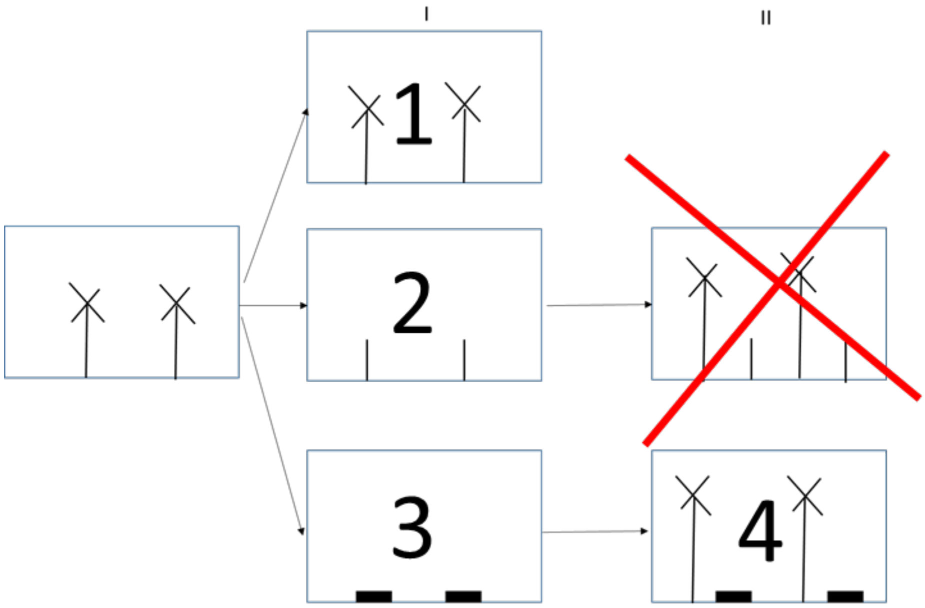

Figure 4.1. Illustration of the four decommissioning scenarios as analysed in this study.

Revisiting Dannheim *et al.* (2020) cause-effect relationships: proof-of-concept

Both proof-of-concept exercises demonstrated the anticipated methodology worked and hence is worth pursuing (draft technical reports available upon request). For all CERs, both proof-of-concepts succeeded in addressing the questions whether CERs changed (0/1) and if yes, in what direction (+/-) and how much (--/--/0/+/++).

Considerations relevant for future work are:

- The questions of realism of making assessments of the CER when not considering the use of the space after decommissioning, e.g. change in fishery use or shipping/transport routes.

- The comprehensiveness and correctness of literature documenting that requires checking.
- That some CER pathways were described in the main text of Dannheim *et al.* (2020), rather than the supplementary material.

4.5 Suggestions for future work

With proof-of-concepts having been successful, we propose to run the full assessment of decommissioning effects in a next cycle of WGMBRED.

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VI Biodiversity Information System of benthic species at ARtificial structures (BISAR)

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VII Decommissioning of offshore wind farms and its impact on benthic ecology

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Decommissioning of offshore wind farms and its impact on benthic ecology

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ABSTRACT

At the end of their operational life time offshore wind farms need to be decommissioned. How and to what extent the removal of the underwater structures impairs the ecosystem that developed during the operational phase of the wind farm is not known. So, decision makers face a knowledge gap, making the consideration of such ecological impacts challenging when planning decommissioning. This study evaluates how complete or partial decommissioning of foundation structure and scour protection layer impacts local epibenthic macrofauna biodiversity. We assessed three decommissioning alternatives (one for complete and two for partial removal) regarding their impact on epibenthic macrofauna species richness. The results imply that leaving the scour protection layer in situ will preserve a considerable number of species while cutting of the foundation structure above seabed will be beneficial for the fauna of such foundation structures where no scour protection is installed. These results should be taken with a grain of salt, as the current data base is rather limited. Data need to be improved substantially to allow for reliable statements and sound advice regarding the ecological impact of offshore wind farm decommissioning.

1. Introduction

Construction and operation of offshore wind farms (OWF) affect the marine ecosystem (Dannheim et al., 2020; Degraer et al., 2019; Zupan et al., 2023). In an area that is otherwise impaired by intense trawl fishery, OWF provide retreats for fish and new habitats for hard-substrate associated organisms (Coolen et al., 2020b; Fowler et al., 2019; Lacey and Hayes, 2020; Lefaible et al., 2019). Such benthic communities develop and change in structure and composition over the operational phase of an OWF and develop valuable miniature ecosystems (Dannheim et al., 2020; de Mesel et al., 2015; Degraer et al., 2019; Zupan et al., 2023). At the end of their operational life-time OWF, however, need to be decommissioned (removed). The dismantling of the underwater structure most likely impacts hard-substrate associated species and might even result in the complete elimination of their habitat, if foundation structures were removed entirely. Decisions on how to decommission OWF, hence, directly impact the maintenance of the associated benthic community.

According to Jackson and Miller (2009) an artificial reef 'is a submerged structure placed on the seabed deliberately, to mimic some characteristics of a natural reef'. Historically the predominant reef structures in Southern North Sea were oyster reefs, stones and rocks as well as moorlog (Olsen, 1883), which have been largely lost due to overharvesting and trawl fishery (Coolen, 2017). Even though OWF are not artificial reefs following the definition of Jackson and Miller (2009), they are well known for their artificial reef effect in the North Sea (Dannheim et al., 2020; de Mesel et al., 2015; Degraer et al., 2019). After installation the underwater structures are colonised by hard-substrate associated species (Dannheim et al., 2017). Time since construction, material, surface orientation, salinity, sea water temperature, food availability, wave action, water current speed or direction, turbidity, light and shadows as well as the proximity of other reefs providing a source of larvae may affect the taxonomic composition of this community (Coolen et al., 2020b, Baeye and Fettweis, 2015). The vertical dimension of the installations itself also affects these benthic communities in their structure and diversity. The foundation structures exhibit a clear zonation (splash zone, intertidal zone and deep subtidal zone) each hosting a different community (de Mesel et al., 2015). However,

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these community are not distributed evenly along the structures. Coolen et al. (2020b) and van der Stap et al. (2016) report non-linear relationships between water depth and species richness at oil and gas platforms. The structural design of the foundation has a considerable influence on the communities as well. When investigating benthic megafauna at the OWF *alpha ventus* and *Riffgat,* Krone et al. (2017) found that community composition differed at the three different foundation types (monopiles, tripods and jackets), and Coolen et al. (2020b) showed that species composition is influenced by substrate types, too. Particularly the scour protection layer seems to be a valuable habitat for hard-substrate dwelling species (Coolen et al. 2019, 2020a; Fowler et al., 2019).

OWF consist of multiple wind turbines that sit on foundation structures. There are different foundation types; across Europe, monopiles made up more than 80% of the foundations in 2020, the remainder was mainly jackets and gravity-base foundations (Ramírez et al., 2021). Monopiles and gravity-base foundations are often surrounded by a scour protection layer often using rock armour consisting of gravel, quarry run stone, limestone or granitic blasted rock (Esteban et al., 2019; Whitehouse et al., 2011). The wind turbines are connected by inter-array cables that are usually merged on an offshore sub-station. Up to date, only six OWF were decommissioned (Herzig, 2021). These OWF were all small in wind turbine size and number and located near-shore in shallow waters. Hence, currently we lack experience in large scale OWF decommissioning and its effects on the marine environment (Birchenough and Degraer, 2020; Fowler et al., 2019). Decision-makers of OWF decommissioning thus have no reliable knowledge base for their decisions. This paper addresses this knowledge gap by presenting a case-study of the impact of different decommissioning alternatives on the associated epibenthic macrofauna biodiversity based on the available data sampled at OWF throughout Europe.

Eckardt et al. (2022) predict an increase of OWF decommissioning from 2025 onwards, with a large increase in the 2030's. Hence, decommissioning of the already installed OWF, but also proactive decommissioning planning for newly installed OWF, will become a pressing issue in OWF management in the near future. In 2020 the majority of offshore wind turbines installed in Europe had a capacity of 8–8.4 MW and 9.5 MW, respectively (Ramírez et al., 2021). Those OWF that face decommissioning soon, however, consist of about 80 turbines of an older generation each with a nominal power of 3–4 MW (Eckardt et al., 2022). So far, there is no standardized procedure for the decommissioning of OWF across Europe. Even though there is an agreement, that the turbines need to be removed and the foundation structures are cut at or below seabed, there is no clear consensus whether inter-array cables and the scour protection is to be removed (Britton, 2013; Drew, 2011; Eckardt et al., 2022; Stephenson, 2013).

This paper focuses on how the scope of OWF decommissioning affects the epibenthic macrofauna biodiversity. If OWF are decommissioned completely, the 'added' hard-substrate associated benthic biodiversity will be lost completely (Smyth et al., 2015), while partial decommissioning may maintain the increased overall benthic biodiversity (Coolen et al., 2020a; Fowler et al., 2019). This study aims to investigate how different scopes of decommissioning (i.e., complete removal, leaving scour protection layer in situ and/or cutting the foundation structure above seabed) impact epibenthic macrofauna biodiversity. In accordance with Coolen et al. (2020b) and van der Stap et al. (2016) we expect a non-linear relationship between water depth and species richness. As the scour protection layer is much more complex than straight steel monopiles we hypothesized to find a larger biodiversity there. Even though Coolen et al. (2020b) were not able show this effect for oil and gas platforms, we still make this assumption here. As the species composition differed between the steel structures and the rocky surroundings (Coolen et al., 2020b), we are interested in the species overlap and the uniqueness of species at the scour protection layer and foundation structure.

2. Material and methods

2.1. Data base

Our study used the BISAR (Biodiversity Information System of benthic species at ARtificial structures) dataset on OWF associated epibenthic macrofauna communities (*fide* (Dannheim et al)). We accessed these data through the Alfred-Wegener-Institute AWI Biodiversity information system 'CRITTERBASE' (Teschke et al., 2022). Data were selected based on the following criteria: (1) from offshore wind farms (OWF) and the research platform *FINO 1*, as its foundation structure equivalates to those of offshore wind turbines; (2) from foundation or scour protection layer; and/or (3) within sampling depth range from foundation up to 5 m above seabed. Five projects (*BelWind, C-Power, FINO 1, Princess Amalia* and *Horns Rev 1*) with 15 locations in four European countries suited the criteria (Table 1, Fig. 1). Foundation types include monopiles, gravity-base foundations and a jacket. Maximum sampling depth at the foundations ranged from 8 to 30 m and at the scour protection layer from 10 to 30 m. On the foundation scrape samples were collected. The scour protection layer was sampled by collecting or scraping. For locations PA1, PA20, PA45 and PA60 information on sampled area was missing. This information was provided by (Faasse, 2021) (Table 2).

The data of the different projects were combined into a single data set and pre-processed to achieve a consistent taxonomic representation on the lowest taxonomic level in the following way: (i) Multiple entries of the same species (AphiaID) within the same sample were pooled (ii) Simultaneous entries of different taxa (e.g., species *Urticina felina* and genus *Urticina*) were merged on the lowest taxon. (iii) In case of simultaneous entries of higher taxonomic levels and of several lower taxonomic levels, the numbers referring to the higher levels were distributed proportionally among the lower levels (Coolen et al. 2020a, 2020b). We identified 330 taxa in total, of which 219 were defined on species level, 51 on genus level and 30 on family level.

The distance from seabed was calculated as the difference between water depth and sampling depth. Water depth of the OWF *BelWind*, *C-Power*, *Princess Amalia* and *Horns Rev 1* was assumed to be equivalent to the maximal sampling depth at the scour protection layer. At *Fino 1* water depth is 30 m (Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH, 2022). Community age was calculated in months from installation date to sampling date. For this, Julian counts for these dates were calculated with the Julian function of the R package date (Therneau et al., 2022). In order to control for seasonal effects, Julian dates starting with 1 on January 1st using the format function were calculated.

Taxonomic richness (hereafter referred to a species richness) as number of unique lowest taxa per sample were calculated with help of the rarefy function of the R package vegan (Oksanen et al., 2022). The function calculates 'the expected species richness in random subsamples of size *sample* from the community'. In order to account for different sampled areas, *sample* was set to be a scaled abundance (Ab_{sc}), i.e., the product of the ratio of the sampled area (SA) per sample to the smallest sampled area and the observed abundance (Ab_{obs}) of the sample.

$$Ab_{sc} = \frac{\min(SA)}{SA} * Ab_{obs}$$

2.2. Decommissioning alternatives

Our study examines three decommissioning alternatives: (I) The scour protection layers are removed (if installed) and foundations are cut 1 m below seabed. This alternative reflects the general maximal decommissioning requirements, e.g., in Germany. (II) The scour protection layers are left in situ (if installed) and foundations are cut 1 m below seabed. This alternative reflects decommissioning considerations as for example in the UK (Britton, 2013; Drew, 2011; Stephenson, 2013)

Table 1
Characteristics of the OWF projects selected for analysis.

Project	Country	Location	Water depth	Year commissioned	Years sampled	Sample type	Foundation type
BelWind	Belgium	BW2	30 m	2009	2010–2014	Foundation	Monopile
						Scour protection	–
		BW8	30 m	2009	2013, 2015, 2017, 2018	Foundation	Monopile
						Scour protection	–
C-Power	Belgium	CP5	30 m	2008	2009–2015, 2019	Foundation	Gravity-base
						Scour protection	–
		CP6	30 m	2008	2010, 2012, 2013, 2016, 2018	Foundation	Gravity-base
						Scour protection	–
Fino 1	Germany	FINO	30 m	2003	2005–2007	Foundation	Jacket
Princess Amalia	Netherlands	PA1	23 m	2007	2011, 2013	Foundation	Monopile
						Scour protection	–
		PA20	21 m	2006	2011, 2013	Foundation	Monopile
						Scour protection	–
		PA45	24.5 m	2007	2011, 2013	Foundation	Monopile
						Scour protection	–
		PA60	23.5 m	2007	2011, 2013	Foundation	Monopile
						Scour protection	–
Horns Rev 1	Denmark	HR33	10 m	2002	2003–2005	Scour protection	–
		HR55	10 m	2002	2003–2005	Scour protection	–
						Foundation	Monopile
		HR58	10 m	2002	2003–2005	Scour protection	–
						Foundation	Monopile
		HR91	10 m	2002	2003–2005	Scour protection	–
		HR92	10 m	2002	2003–2005	Scour protection	–
		HR95	10 m	2002	2003–2005	Scour protection	–
						Foundation	Monopile

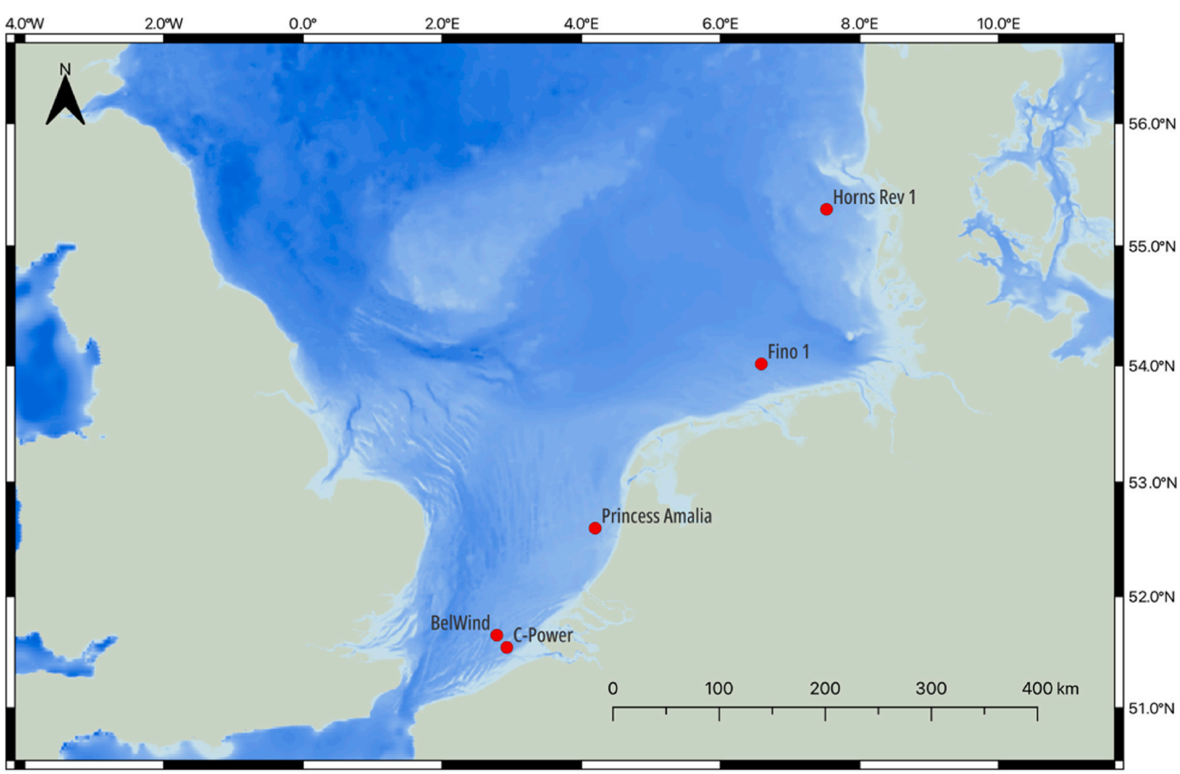

Fig. 1. Locations of the analysed offshore wind farms and research platform (red dots) in the North Sea.

and enables analysis of impacts on the epibenthic macrofauna biodiversity by maintaining some of the hard-substrate structures. (III) The scour protection layers are left in situ (if installed) and foundations are cut at 5 m above seabed, allowing to analyse the effect of maintaining hard-substrate structures above sea bed level. For all decommissioning alternatives it is assumed that foundation structures are cut with abrasive water jet cutting from the inside and inter-array cables are removed.

Other partial decommissioning alternatives such as 'topping', where parts or the complete structures are placed on the seabed as suggested by Fowler et al. (2019), are deemed unlikely for the North Sea under the current policy regime and considering future expansion targets.

2.3. Analyses

The data set consists of the following variables. Species richness is the response variable. Categorical variables are the location (with 15

Table 2
Information on benthic sampling locations and area within each OWF project.

Project	Location	Sample type	Sampled area per sample	Reference
BelWind	BW2 and BW8	Foundation	0.0625 m^2	Kerkhof et al., (2022)
		Scour protection	0.0435 and 0.082 m^2	Kerkhof et al., (2022)
C-Power	CP5 and CP6	Foundation	0.0625 m^2	Kerkhof et al., (2022)
		Scour protection	0.0232 and 0.192 m^2	Kerkhof et al., (2022)
Fino 1	FINO	Foundation	0.04 m^2	Schröder et al., (2008)
Princess Amalia	PA1, PA20, PA45 and PA60	Foundation	0.056 m^2	Coolen et al., (2020a)
		Scour protection	0.21 m^2	(Faasse, 2021)
Horns Rev 1	HR33, HR55, HR58, HR91, HR92 and HR95	Foundation and scour protection	0.04 m^2	Leonhard and Frederiksen (2006); Leonhard and Pedersen (2004)

levels, one for each foundation), sample type (with the two levels foundation and scour protection layer) and foundation type (with the three levels monopile, jacket and gravity-base foundation). Continuous variables are distance from seabed in meters, seasonality as day of the year and community age in months. Data exploration was conducted according to the protocol of Zuur et al. (2010). Species richness across all data points was assumed to follow a Poisson distribution. Cleveland's dotcharts (Cleveland, 1985) were used to check for outliers in the continuous variables. Boxplots were created to inspect the relation of the categorical variables and the response variable. A Pearson's Chi-squared test (Patefield, 1981) was conducted to test for dependency between sample type and foundation. To visually inspect continuous variables and to test for correlation, *ggscatter* of the *ggpubr* package (Kassambara, 2020) with method *kendall* for calculating correlation coefficients was used. For the entire data set considering all locations, the continuous variables (seasonality, distance from seabed and community age) are only weakly correlated with each other (seasonality and distance from seabed: correlation coefficient = 0.086, p-value <0.05, community age and distance from seabed: correlation coefficient = 0.059, p-value <0.05, seasonality and community age: correlation coefficient = 0.21, p-value <0.05).

We conducted the following analyses: (1) comparison of species richness at the scour protection layer and the entire location of different foundation types, (2) analysis of impact of distance from seabed on species richness and (3) investigation of impact of decommissioning alternatives on epibenthic macrofauna biodiversity (Table 3).

(1) Kruskal-Wallis rank sum tests were conducted to test for differences in species richness between gravity-base foundations and monopiles at the scour protection layer and the entire foundation structure. The 14 locations with scour protection layer were used to calculate species richness at the scour protection layer. All locations were used to calculate the species richness of the entire location, i.e., scour protection layer and foundation structure.

(2) In order to account for non-linear relationships, generalised additive mixed models (GAMM) were created using the mgcv package (Wood, 2011) to analyse effects of distance from seabed on species richness. For this analysis, only data sampled at the foundation structures was considered. Decommissioning alternative III assumes that foundation structures are cut at 5 m above seabed, hence, only such locations were considered at which samples were collected on the foundation up to 5 m above seabed. Location CP5 fulfils these criteria, but it was excluded as only a single sample was collected at the foundation structure up to 5 m above seabed and it was the only location with a gravity-base foundation. Hence, the number of samples was too low for running a GAMM. FINO, the only location with a jacket, on the other hand, was included in the analysis, as 64 samples were collected at the foundation structure up to 5 m above seabed. In total, five locations, one jacket (FINO) and four monopiles (PA20, HR55, HR58 and HR95) were suitable for further analysis (Table 3). As species richness was significantly higher at the jacket (Kruskal-Wallis rank test, Chi-squared = 94.4, df = 1, p-value <0.0001), GAMM were created for the two foundation types separately. The continuous variables (seasonality, distance from seabed and community age) of the data sets were visually inspected and tested for correlation following the same procedure as outlined above. The continuous variables of both data sets are only weakly correlated with each other (for monopiles: seasonality and distance from seabed: correlation coefficient = 0.048, p-value = 0.25, community age and distance from seabed: correlation coefficient = −0.11, p-value = 0.0076, seasonality and

Table 3
Number of samples (n) per location from the scour protection layer and from the entire foundation at different distances from seabed. 'x' indicates that the location was used in the analysis: (1) comparison of species richness at the scour protection layer and the entire location of different foundation types, (2) analysis of impact of distance from seabed on species richness and (3) investigation of impact of decommissioning alternatives on epibenthic macrofauna biodiversity.

Project	Location	Scour protection layer		n on foundation per distance from seabed													Used in analysis		
		n	Depth in m	0 m	1 m	2 m	3.8 m	4 m	4.7 m	4.9 m	5 m	>5–10 m	>10–15 m	>15–20 m	>20–25 m	>25 m	(1)	(2)	(3)
BelWind	BW2	6	30	–	–	–	–	–	–	–	–	–	29	–	–	–	x	–	–
	BW8	3	30	–	–	–	–	–	–	–	–	–	23	–	–	–	x	–	–
C-Power	CP5	20	30	–	–	–	–	–	–	–	1	4	65	3	3	1	x	–	x
	CP6	6	30	–	–	–	–	–	–	–	–	3	16	–	5	–	x	–	–
Fino	FINO	–	–	29	1	–	–	4	–	–	30	32	10	39	37	36	–	x	x
Princess Amalia	PA1	3	23	–	–	–	–	–	–	–	–	4	4	4	7	–	x	–	–
	PA20	3	21	–	–	–	–	4	–	–	–	–	4	8	4	–	x	x	x
	PA45	4	24.5	–	–	–	–	–	–	–	–	4	4	4	8	–	x	–	–
	PA60	3	23.5	–	–	–	–	–	–	–	–	4	4	4	8	–	x	–	–
Horns Rev	HR33	72	10	–	–	–	–	–	–	–	–	–	–	–	–	–	x	–	–
	HR55	96	10	–	–	12	12	12	–	–	–	66	–	–	–	–	x	x	x
	HR58	97	10	–	–	12	–	12	–	12	–	56	–	–	–	–	x	x	x
	HR91	72	10	–	–	–	–	–	–	–	–	–	–	–	–	–	x	–	–
	HR92	71	10	–	–	–	–	–	–	–	–	–	–	–	–	–	x	–	–
	HR95	96	10	–	–	14	–	10	12	–	–	60	–	–	–	–	x	x	x

community age: correlation coefficient = 0.076, p-value = 0.081, for the jacket seasonality and distance from seabed: correlation coefficient = −0.028, p-value = 0.58, community age and distance from seabed: correlation coefficient = −0.056, p-value = 0.26, seasonality and community age: correlation coefficient = 0.35, p-value <0.0001). A Poisson distribution with log link was used for the GAMM. Location (*i*) was considered as random effect in the GAMM of the monopiles to account for spatial pseudo-replication. To account for seasonal effects, sampling dates as Julian dates of the year were included. Community age in months was also included in the model. Distance from seabed, community age and seasonality were considered as smoothing terms (*f*()). The variables were included in different combinations (Table 5). The formula for the model considering all variables is:

$$\ln(\text{species richness}_{ij}) = \alpha + f(\text{distance from seabed}_{ij}) + f(\text{community age}_{ij}) + f(\text{seasonality}_{ij}) + \text{location}_j + \varepsilon_{ij}$$

The residuals ε_i of the best fitting models were assumed to approach normal distribution with mean of 0 and variance of σ.

The number of basis functions of the smooth terms were adjusted to enable 'potential variation in the smoother' (Pedersen et al., 2019). For seasonality they were set to 3, due to an assumed bell-shaped pattern throughout the year, with low values in winter that increase during spring, reaching top-values in summer and a decrease in fall (Coolen et al., 2022). Due to small k-index values, for the smoothing terms community age and distance from seabed, k was set to the largest value possible (community age: for monopiles k = 8 and for jacket k = 11, sampling depth: for monopiles k = 20 and for jacket k = 9). This corresponds to the maximum number of unique community ages and depths, respectively, sampled. AIC (Akaike's Information Criterion) values were calculated to identify the best fitting model (Akaike, 1973).

(3) In order to investigate the impact of the decommissioning alternatives on the epibenthic macrofauna biodiversity, the underwater construction of the wind turbines was subdivided into the following sections: A: scour protection layer, B: scour protection layer and foundation structure up to 5 m above seabed and C: foundation structure beyond 5 m above seabed. Only locations were considered that were sampled at 0–5 m above seabed and at the scour protection layer. The location FINO has a jacket foundation without scour protection but was also included in the analysis. In order to assess the impact of decommissioning alternatives on the epibenthic macrofauna biodiversity, (i) the percentage of species maintained per section and (ii) species overlap as well as uniqueness of species per section were analysed and (iii) decommissioning alternatives were compared. Species overlap as well as unique species per section was investigated by creating Venn diagrams for each location using the *eulerr* package (Larsson, 2020). The percentage of species maintained was calculated as the proportion of species (and lowest taxon, respectively) per section, i.e., the scour protection layer and/or the foundation structure up to 5 m above seabed, in relation to the total number of species per location, i.e., the scour protection layer and the entire foundation structure. To test for the influence of the decommissioning alternatives on the percentage of species maintained, a Dunn's test was performed (R Core Team, 2019).

3. Results

For a general overview, species richness as number of species per sample for the scour protection layer and the entire location, i.e., the scour protection layer and the foundation structure, are presented in Table 4 and Fig. 2. A list of taxa identified per location is provided as supplementary material.

3.1. Comparison of species richness at the scour protection layer and the entire location of different foundation types (1)

Species richness per sample varies among the different foundation types, but does not differ between the entire location (foundation structure and scour protection layer) and scour protection layer only (Fig. 3). Species richness is significantly higher at gravity-base foundations than at monopiles, both for the entire location (Chi-squared = 231.43, df = 1, p-value <0.001) and at the scour protection layer only (Chi-squared = 71.07), df = 1, p-value <0.001). On gravity-base foundations species richness does not differ significantly (Chi-squared = 2.196, df = 1, p-value = 0.139) between scour protection layer (mean ± SD: 12.6 ± 2.4, median: 12.5, IQR: 2.3, n: 26) and the entire location (mean ± SD: 11.5 ± 2.7, median: 11.9, IQR: 3.6, n: 127). At monopiles species richness is significantly (Chi-squared = 10.402, df = 1, p-value = 0.0013) lower at the scour protection layer (mean ± SD: 5.6 ± 1.9, median: 5.6, IQR: 2.4, n: 526) than at the entire location (mean ± SD: 6.2 ± 2.5, median: 5.9, IQR: 2.7, n: 946).

3.2. Analysis of impact of distance from seabed on species richness (2)

Generalised additive mixed models (GAMM) were conducted to investigate the relationship between species richness and distance from seabed for monopiles and the jacket (Table 5). Based on the Akaike information criterion (AIC), the model (Model = GAMM_J_4, AIC = 83.25) considering all three smoothing terms (distance from seabed, seasonality and community age) fits the jacket data best. For monopiles, the

Table 4
Total number of species, species richness as rarefied number of species per sample (mean ± standard deviation (SD)) at the scour protection layer and for the entire location (foundation and scour protection layer).

Project	Location	Foundation type	Scour protection layer			Entire location		
			Total	Mean	SD	Total	Mean	SD
BelWind	BW2	monopile	54	9.9	4.0	99	8.8	4.2
	BW8	monopile	39	11.9	1.6	92	8.7	3.3
C-Power	CP5	gravity-base foundation	87	12.4	2.5	141	11.5	2.8
	CP6	gravity-base foundation	48	13.2	1.9	82	11.4	2.7
Fino 1	FINO	jacket	–	–	–	115	7.9	2.3
Princess Amalia	PA1	monopile	39	10.4	1.7	83	10.7	4.1
	PA20	monopile	23	5.3	0.6	73	8.8	3.3
	PA45	monopile	45	10.0	3.7	84	9.2	2.7
	PA60	monopile	35	7.9	0.8	79	10.5	3.1
Horns Rev 1	HR33	monopile	48	5.3	1.9	48	5.3	1.9
	HR55	monopile	47	5.7	1.7	54	5.6	1.7
	HR58	monopile	55	5.7	1.9	61	5.6	1.9
	HR91	monopile	35	4.8	1.2	35	4.8	1.2
	HR92	monopile	42	5.4	1.6	42	5.4	1.6
	HR95	monopile	49	5.6	1.4	65	5.8	1.5

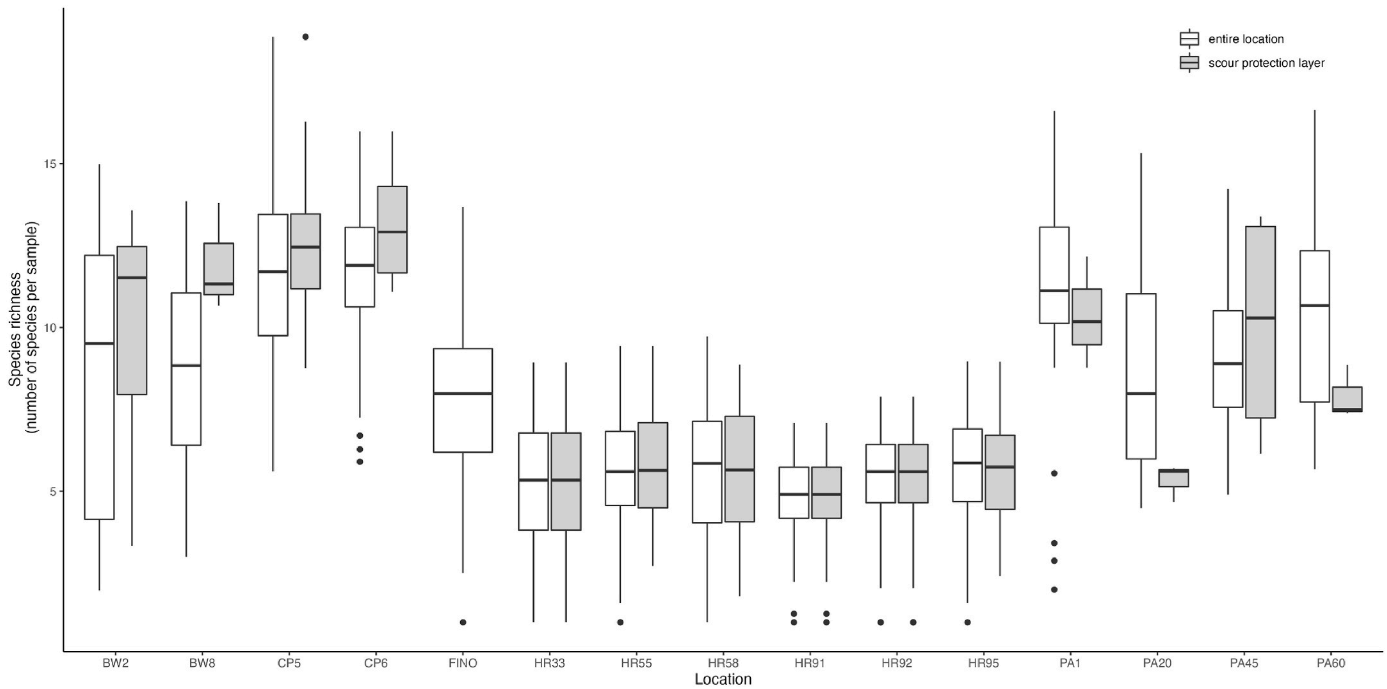

Fig. 2. Species richness as rarefied number of species per sample at the scour protection and the entire location (foundation structure and scour protection layer).

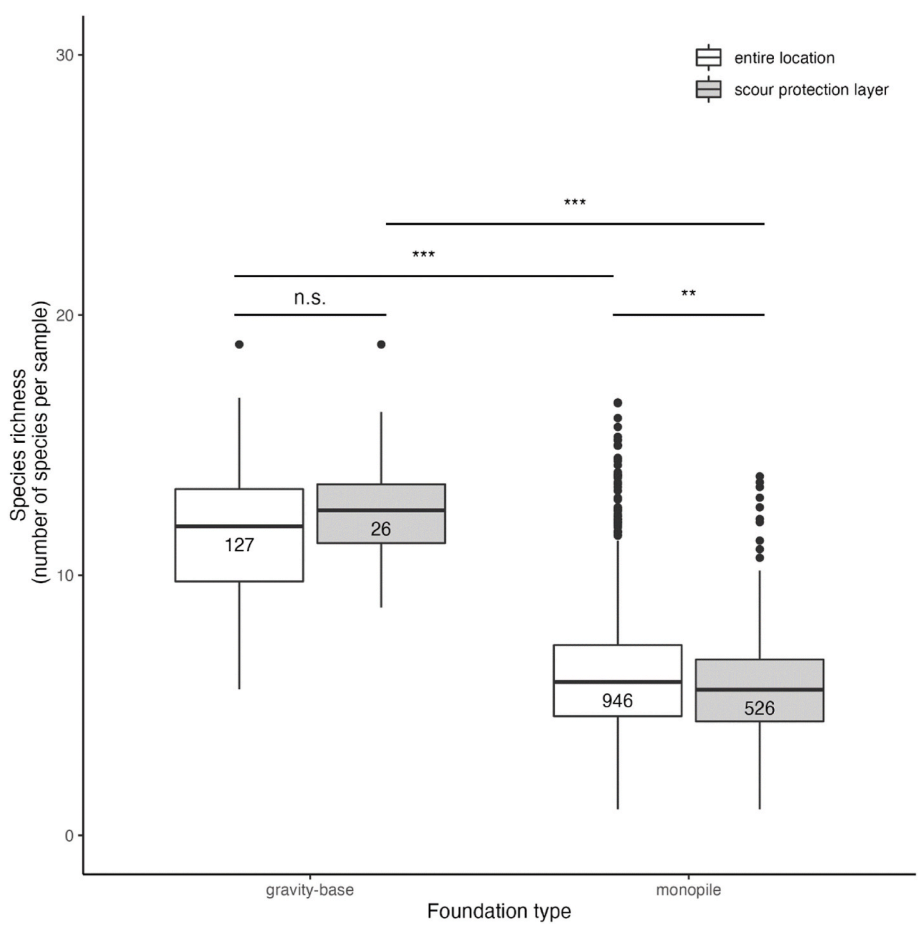

Fig. 3. Species richness at the entire location (foundation and scour protection layer) as well as at the scour protection layer only for gravity-base foundations and monopiles (numbers in the boxes indicate number of observations per group, horizontal lines above the whiskers indicate variables that are compared) with p-values $p < 0.001$: ***, $p < 0.01$: **, $p < 0.05$: *, $p > 0.1$: n.s (not significant).

Table 5
Residual degrees of freedom (Res.df) and Akaike information criterion (AIC) of general additive mixed models (GAMM) considering distance from seabed, seasonality, community age and/or foundation type (x = term is considered, - = term is not considered).

Foundation type	Model	Smoothing terms			Res.df	AIC
		Distance from seabed	Seasonality	Community age		
Monopile	GAMM_MP_1	X	–	–	304.04	199.86
	GAMM_MP_2	X	X	–	302.91	185.03
	GAMM_MP_3	X	–	X	298.95	195.37
	GAMM_MP_4	X	X	X	299.94	187.14
Jacket	GAMM_J_1	X	–	–	215.83	108.59
	GAMM_J_2	X	X	–	211.01	96.09
	GAMM_J_3	X	–	X	209.00	87.61
	GAMM_J_4	X	X	X	210.69	83.25

model with the best AIC values (model = GAMM_MP_2, AIC = 185.03) was not applied, as residuals did not approach normal distribution. Instead, the model considering all smoothing terms that has only slightly higher AIC (model = GAMM_MP_4, AIC = 187.14) was selected. Therefore, models that consider distance from seabed, seasonality and community age for both foundation types are presented.

The summary of the model for the monopiles (GAMM_MP_4) shows that all three smoothing terms are non-linear and significant (Table 6; $p < 0.001$). Species richness is only slightly decreasing up to about 5 m above seabed (Fig. 4). Thereafter, there is a drop of species richness up to about 10 m above seabed where it evens out. The relationship of species richness and community age is quite constant up to an age of about 40 months. Thereafter, species richness increases with the age of the community, albeit with rising uncertainty.

The summary of the model for the jacket (GAMM_J_4) indicates that only the effects of community age and seasonality are non-linear and significant (Table 6; $p < 0.01$). The effect of distance from seabed is linear and mean species richness remains constant over the entire length of the foundation structure (Fig. 5). Species richness increases with community age up to an age of about 20 months, stays almost constant until an age of 45 month and decreases thereafter. The relationship between seasonality and species richness is only minorly non-linear and with a slightly increasing trend.

3.3. Investigation of impact of decommissioning alternatives on epibenthic macrofauna biodiversity (3)

3.3.1. Percentage of species maintained per section (i)

The number and percentage of species found per section and location in relation to the entire location are given in Table 7. On average (±SD) 69.16 ± 23.84% of the species are found on the scour protection layer (section A), ranging from 31.51% (23 of 73 species) at PA20 to 90.16% (55 of 61 species) at HR58. The mean percentage of species found on the scour protection layer and on the foundation structure up to 5 m above seabed (section B) was highest (78.24 ± 15.71%) compared to the other two sections (A and C). The percentage of species found on the foundation structure beyond 5 m above seabed (section C) is on average (74.70 ± 10.41%) lower than in section B but higher than in section A. PA20 is the only location where the percentage species per scour protection layer and foundation up to 5 m (section B) is clearly lower (56.16%) compared to section C (87.67%).

Table 6
Effective degrees of freedom (edf) and p-values of the smooth terms of the GAMM GAMM_MP_4 and GAMM_J_4.

Smooth term	GAMM_MP_4		GAMM_J_4	
	edf	p-value	edf	p-value
Distance from seabed	4.122	<0.001	1.000	n.s.
Community Age	2.303	<0.001	3.765	<0.001
Seasonality	1.638	<0.001	1.767	<0.01

3.3.2. Species overlap and uniqueness of species per section (ii)

The number of species identified on the scour protection only, ranged from 6 species at PA20 (n = 3) to 25 species at CP5 (n = 20) (Table 3 and Fig. 6). At CP5 and PA20 large amounts of species were exclusively found on the foundation structures beyond 5 m above seabed (CP5: 51 species, n = 76; PA20: 32 species, n = 16). This share was smaller at HR55 (5 species, n = 66), HR58 (2 species, n = 56) and H95 (10 species, n = 60). The Venn diagrams (Fig. 6) indicate a strong overlap in species composition between foundation structure and scour protection layer with some species exclusively present in either section at the locations HR55, HR58 and HR95. Species overlap between sections was smallest at location CP5 and the location had the highest number of unique species occurring only at the scour protection layer as well as at the foundation beyond 5 m above seabed. At PA20 the overlap of species on scour protection layer and foundation is the smallest and there are no unique species at foundation up to 5 m above seabed. At FINO, the jacket, no scour protection layer was installed. Here, foundation species inventories below and beyond 5 m overlap distinctly and the number of species unique to the individual sections are distributed evenly.

3.3.3. Comparison of decommissioning alternatives (iii)

Decommissioning alternatives II (69.16 ± 23.84% species richness maintained) and III (78.24 ± 15.71% species richness maintained) do not differ significantly from each other, but both differ significantly from decommissioning alternative I (0%) (Dunn's test comparison of decommissioning alternatives: I vs. II: p-value = 0.020, I vs. III: p-value = 0.004, II vs. III: p-value = 0.624) (Table 8).

4. Discussion

Our study indicates that decommissioning strategies differ in their ecological impact, i.e., the way they cause loss or maintenance of epibenthic macrofauna biodiversity. Complete decommissioning has the most negative effect, obviously, as all hard bottom fauna will be lost. Partial decommissioning preserves more than two thirds of the hard bottom fauna (Table 8). Leaving the scour protection layer in place is the deciding measure, while keeping parts of the foundation structure adds little further biodiversity.

In the following we will (i) take a critical view on the limitations of our data and methods, (ii) discuss our findings in greater detail, (iii) explore further aspects of the ecological relevance of OWF decommissioning and (iv) evaluate possible recommendations for decommissioning management.

4.1. Limitations of data and methods

An underlying challenge of this analysis is the poor data basis with regard to the number of suitable samples. Undoubtedly the BISAR dataset available through CRITTERBASE represents the best data collection on European OWF fouling communities in terms of data volume, data quality and data harmonisation currently available.

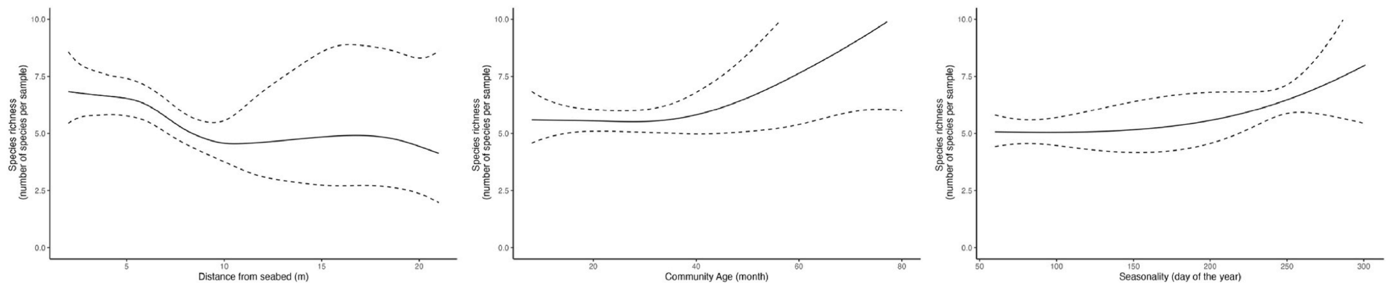

Fig. 4. Relationship between species richness (number of species per sample) and distance from seabed (m), community age (month) and seasonality (day of the year) for monopiles (solid lines) and 95% confidence intervals (dashed lines) (estimates derived from model GAMM_MP_4).

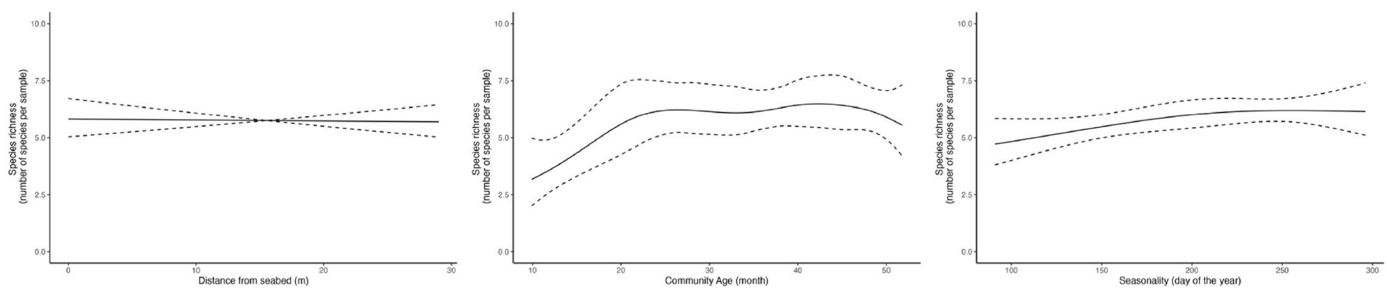

Fig. 5. Relationship between species richness (number of species per sample) and distance from seabed (m), community age (month) and seasonality (day of the year) for the jacket (solid lines) and 95% confidence intervals (dashed lines) (estimates derived from model GAMM_J_4).

Table 7
Number (n) and percentage (%) of species per section in relation to the entire location for each location and mean values and standard deviation (SD) per section.

Location	Entire location		A: Scour protection layer		B: Scour protection layer and foundation up to 5 m above seabed		C: Foundation beyond 5 m above seabed	
	n	%	n	%	n	%	n	%
CP5	141	100.00	87	61.70	90	63.83	115	81.56
FINO	115	100.00	–	–	89	77.39	89	77.39
PA20	73	100.00	23	31.51	41	56.16	64	87.67
HR55	54	100.00	47	87.04	49	90.74	38	70.37
HR58	61	100.00	55	90.16	59	96.72	35	57.38
HR95	65	100.00	49	75.38	55	84.62	48	73.85
Mean ± SD:		100.00 ± 0.00		69.16 ± 23.84		78.24 ± 15.71		74.70 ± 10.41

Nevertheless, it does not meet all requirements to provide fully reliable answers to the question under concern. One of the reasons for this is the distinct methodical heterogeneity of national ecological OWF monitoring programmes. They vary e.g., in sample type (foundation and scour protection), sampling area, depth and duration (Bundesamt für Seeschifffahrt und Hydrographie, 2013; Degraer et al., 2013; Coolen et al., 2020b).

Furthermore, OWF vary structurally, e.g., regarding the design of foundation types as well as their environmental setting, such as water depth, currents, distance to shore. In order to account for the influence of all these variables on, e.g., species richness, a very large number of samples is required. For this analysis data of only a single jacket, two gravity-base foundations in a single OWF and 12 monopiles in three OWF were suitable. The water depth at the monopiles spans a wide range, from 10 to 30 m (and will become more variable as future OWF projects move further offshore). Last but not least, sampling designs differed considerably; at two locations the foundation was only sampled at a water depth of 10 to 15 m and at three locations samples were only collected on the scour protection layer. The insufficient and inconsistent monitoring programmes impairs the validity of our analysis to some extent, and thus, any advice on decommissioning derived from this study should be taken with a grain of salt.

4.2. *Impact of decommissioning on epibenthic macrofauna biodiversity*

Various authors found an overall increase in species richness by offshore installations in an otherwise soft-sediment environment (Coolen et al., 2020b; Fowler et al., 2019; Lacey and Hayes, 2020; Lefaible et al., 2019). This can be deduced to the artificial reef effect (Dannheim et al., 2020) as these structures provide habitat, food and shelter (Fowler et al., 2019). If all OWF structures were removed completely, this habitat and all species associated would be lost. This is well known from decommissioning of offshore oil and gas installations e.g., van Elden et al. (2022).

Our results show clearly that leaving the scour protection layer in situ will preserve the majority of hard-substrate associated species (69.16 ± 23.84%, Table 8). The scour protection layer of the monopiles can host very high percentages of all species (up to 90.16%, Table 7) and a large proportion of species that is also present in other sections (Fig. 6). Generally, leaving the scour protection layer in situ would preserve many species unique to that section as well as a large proportion of epibenthic macrofauna biodiversity of the entire location (scour protection layer and the foundation structure). A study on the comparison of decommissioning alternatives for the gravity-based structure of a Dutch gas platform revealed that about 26% of the species would be lost, if the concrete gravity-base foundation and the steel structures were removed completely and the rock dump was left in situ or scattered (Coolen et al., 2020a). Furthermore, the increase in the number of hard bottom dwellers, e.g., of edible crab (*Cancer pagurus*), points to a biomass increase associated with the scour protection layer, see Krone et al. (2017) and Coolen et al. (2019). One location in our analysis, i.e., PA20, had a distinctively lower percentage of species at the scour protection layer than all other locations (only 31.5% compared to at least 61.7%, Table 7). This might be related to deeper waters (24.5 m), as

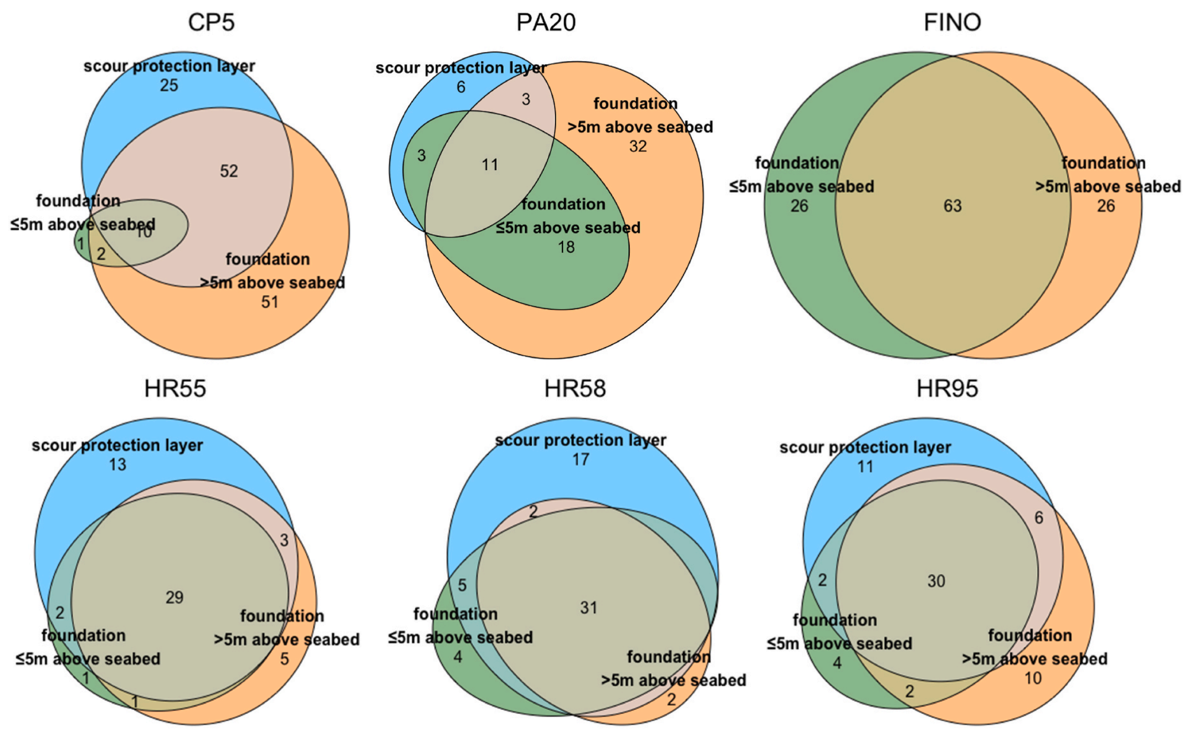

Fig. 6. Venn diagrams for overlap of species between scour protection layer (blue) and foundation structure up to 5 m (green) and beyond 5 m above seabed (orange) for the locations CP5, PA20, FINO, HR55, HR58 and HR95. (Numbers represent the number of species per section and overlap, respectively).

Table 8
Percentage (%, mean ± standard deviation (SD)) of species maintained per decommissioning alternative.

Decommissioning alternative	Scour protection layer	Foundation structure	Percentage of species richness maintained (%) (Mean ± SD)
I	Removed	Cut 1 m below seabed	00.00
II	Left in situ	Cut 1 m below seabed	69.16 ± 23.84
III	Left in situ (if installed)	Cut 5 m above seabed	78.24 ± 15.71

species composition of upper and lower parts of the foundation differ distinctly (Coolen et al. 2020b, 2022).

The relationship of species richness to distance from seabed differed between the different foundation types: at the jacket structures, species richness was constant along the entire vertical structure (Fig. 5), while at monopiles it changed in a non-linear way (Fig. 4), similarly to oil and gas platforms (Coolen et al., 2020b). Marine fouling assemblages on oil and gas platforms in the North Sea showed an increase in species richness down to a water depth of about 15 to 20 m and a decrease beyond this depth (van der Stap et al., 2016). The intermediate disturbance hypothesis (Connell, 1978) may explain these observations, as high biodiversity at intermediate depth is maintained by intermediate disturbances (Coolen et al., 2020b; van der Stap et al., 2016). Fortune and Paterson (2020) argue that this depth effect can also be explained by the competition of dominant species. Our results, however, are not in line with Coolen et al. (2020b), Fortune and Paterson (2020) and van der Stap et al. (2016), as species richness at the monopiles was highest close to the seabed. This might imply that cutting the foundation structures above seabed would considerably contribute to maintaining benthic species richness. Our analysis, however, reveals that this is only true for locations without scour protection layer, i.e., when cutting the jacket up to 5 m above seabed would maintain 77% of the species, thereof 26 unique species and 63 species found also beyond 5 m above seabed (Table 7, Fig. 6). Cutting the monopile and gravity-base foundation structures up to 5 m above seabed will increase the percentage of species that would be maintained only slightly (about 2–9%, without location PA20) compared to leaving the scour protection layer in situ only. Further, there are only a few species present exclusively on the lowest 5 m of the foundation (2 to 6 species per location without PA20, Fig. 6). Accordingly, cutting foundations above seabed when scour protection is present, does not contribute considerably to preserving species richness. This coincides with removal options for oil and gas platforms where less species were present on the steel legs of the structure than on surrounding rock dumps (Coolen et al., 2020a). The community composition was found to also differ between the different foundation types (Krone et al., 2017). Krone et al. (2017) reported differences in fish and crab species inventory on jacket and tripod foundations compared to monopiles, but attributed this not to the different structural design of the foundation, but rather to the scour protection layer present at the monopile only.

4.3. Further aspects of the ecological relevance of OWF decommissioning

In the past, potential impacts on the marine environment were ignored when removing offshore structures. E.g., the Danish OWF *Vindeby* was dismantled completely, although the environmental impact assessment indicated that the removal of the structures could lead to a decline in the Atlantic cod (*Gadus morhua*) ((Nicolaisen et al., 2016) in Fowler et al., 2019). Just as for benthic species OWF provide shelter as well as feeding and nursing grounds for fish species as indicated by an increase in fish abundance (Stenberg et al., 2015; van Hal et al., 2017). Structures close to the seabed are of special importance to juvenile Atlantic cod, as they primarily forage on smaller crustaceans such as amphipods and small crabs which are found on the lower parts of the foundation and on the scour protection layer (Krone et al., 2017; Reubens et al., 2013). Other opportunistic feeders like the pelagic horse mackerel (*Trachurus trachurus*) were found to at least seasonally visit OWF to feed on energy-rich species like *Jassa herdmani* (Mavraki et al., 2021). Also, the fisheries exclusion effect, i.e., the closure for fisheries in and around the OWF, benefits fish communities and allows the seafloor and its communities to recover from intensive trawling (Birchenough and Degraer, 2020). Apparently, OWF alter the local food-web beyond the benthic community, but the implications for the food-web and eventually the OWF decommissioning are not well understood yet.

The impact of OWF structures on the surrounding soft-bottom community is currently not completely understood (Dannheim et al., 2020; Degraer et al., 2019; Hutchison et al., 2020; Lefaible et al., 2019). The area covered by OWF is very small, i.e., only about 1.7% of the total area of the North Sea in 2020, and thus such effects may be negligible on the ecosystem level (Ter Hofstede et al., 2023;2017; Fowler et al., 2019). However, many OWF were built over the past years and more will be installed in the future. How and to what extent soft-bottom communities are impacted by the increased number of OWF and would be affected by partial decommissioning demands further investigations.

Maintaining OWF structures might also have other large-scale impacts e.g., upholding connectivity by providing stepping stones for the dispersal of hard-substrate associated species (Degraer et al., 2020). The potential regional impact of OWF and of their removal, respectively, are neglected in decision-making processes for decommissioning quite often (Fowler et al., 2019). The relevance of the artificial structures for the connectivity of species and communities depends on the uniqueness of the habitat and on their location and distance in relation to other habitats and structures (Fowler et al., 2019). Structures that resemble suppliers, e.g., spawning sites, should not be removed, if the established network functions were to be maintained, as shown for pelagic dispersal and connectivity between hard substrates in the North Sea (van der Molen et al., 2018). The structures, however, might not only enhance connectivity of indigenous species. The vertical structure of OWF resembles an offshore habitat that is usually not present in the North Sea and, hence, may provide a habitat for non-indigenous species (Coolen, 2017; Dannheim et al., 2017; de Mesel et al., 2015). A considerable higher proportion of non-indigenous species were found in the intertidal parts of such structures than at the deeper parts (Coolen et al., 2020b; de Mesel et al., 2015). Consequently, a partial decommissioning in terms of leaving the scour protection in place and cutting foundation structures just a couple of meters above seabed would remove potential habitat for non-indigenous species and, thus, may be considered a defensive measure regarding the dispersal of non-indigenous species. To which extent prevailing OWF structures will affect the connectivity at regional or even larger scales, especially when considering the installation of new OWF, remains to be investigated.

We can see the scour protection layer as an additional valuable benthic habitat that might even host species of conservational interest (Fowler et al., 2019). E.g., a study on subsea pipelines found five such species on the pipes and a further 13 rare taxa in the neighbouring sediment (Lacey and Hayes, 2020). Compared to natural habitats and to decade-old human-introduced structures such as oil and gas platforms, most OWF are comparatively new habitats and the associated community is still relatively young. Coolen et al. (2022) hypothesized that an interplay of inhibition, due to a shortage of spatial resources and consumption of other larvae by early colonisers, and keystone species which increase habitat by facilitating secondary hard substrate, may result in an 'pseudo-equilibrium' at low water depth. Another study, however, was not able to support this theory and rather postulated that the communities are subject to constant change due to the ability to colonise already occupied spaces and the mortality of already present individuals (Zupan et al., 2023). It appears, thus, very challenging to predict how the benthic community will develop over the operational phase of the OWF and whether habitats valuable for species, also of commercial or conservational interest, will persist. Consequently, further research near the end of the operational life time is required to enable more reliable statements regarding the current ecological status of and possible ecological impacts of OWF decommissioning.

4.4. Recommendations for decommissioning management

Due to the patchy data basis currently available, our recommendations for OWF decommissioning regarding its ecological impact leave much to be desired in terms of clarity and reliability. Nonetheless, our results clearly suggest, that if the maintenance of epibenthic macrofauna biodiversity in the OWF area was an objective of decommissioning, then (i) the scour protection layer should be left in situ or (ii) foundation structures without scour protection should be cut above seabed.

However, in order to validate the results of this study and to acquire in-depth knowledge on the cause-effect relationships systematic and long-term surveys are required (Dannheim et al., 2020; Degraer et al., 2019; Fowler et al., 2019), we suggest targeted investigations of decommissioning impacts on:

- epifauna at the scour protection layer and the bottom of the foundation
- surrounding soft-bottom and fish communities
- species of commercial and conservational interest
- overall food-web and
- connectivity of communities

over the entire or at least towards the end of the operational life-time of the OWF turbines, in order to make well-founded recommendations for OWF decommissioning.

This study presents possible impacts of partial decommissioning on the epibenthic macrofauna biodiversity. However, if partial decommissioning is to be considered, other aspects need to be accounted for. (i) With increasing expansion targets for renewable energies (Bundesministerium für Wirtschaft und Klimaschutz, 2022), the subsequent use of the OWF area needs to be considered. Remaining scour protection layer would probably not be an obstacle, but whether foundation structures cut just above seabed would be a problem for new installations depends among others on the new park layout (Eckardt et al., 2022). New foundation structures could probably not be installed in the same locations as the old ones, even if they were removed completely (Eckardt et al., 2022). (ii) Also, partial decommissioning might impair the safety and efficiency of traffic, e.g., foundation structures cut above seabed might be an obstacle for shipping and fishery; how or to what extent, though, remains to be investigated in detail (Eckardt et al., 2022). (iii) Another relevant factor to be considered are the decommissioning costs. Decommissioning alternatives where the scour protection layer is left in situ, are associated with the lowest net costs per MW (Eckardt et al., 2022). However, costs that are potentially associated with continued monitoring of components left in place in offshore areas, are not considered in the calculations stated by Eckardt et al. (2022).

5. Conclusion

The current state of knowledge implies that partial decommissioning of offshore structures – leaving the scour protection layer in situ in particular - is beneficial for the conservation of local hard-bottom dwelling species and overall benthic biodiversity. However, in order to validate our findings and for a better assessment of the impacts of different alternatives of offshore wind farm decommissioning on the ecosystem more data is required. Currently, monitoring programmes vary considerably among European countries, resulting in an inconsistent data set. Especially programmes for investigations of the foundation structure near the seabed and the scour protection towards the end of the operational life are missing. For well-founded predictions of impacts of decommissioning on the whole system, targeted, systematic and long-term surveys of the benthic and fish communities within and around offshore wind farms are required.

CRediT authorship contribution statement

Vanessa Spielmann: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jennifer Dannheim:** Conceptualization, Data curation, Supervision, Validation, Writing – review & editing. **Thomas Brey:** Conceptualization, Supervision, Validation, Writing – review & editing. **Joop W.P. Coolen:** Conceptualization, Data curation, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used will be publically available within the BISAR (Biodiversity Information System of benthic species at ARtificial structures) dataset by the AWI Biodiversity information system CRITTERBASE.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119022.

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Supplementary material to the manuscript

Decommissioning of offshore wind farms and its impact on benthic ecology

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Annex Table 1: List of taxa (AphiaID and scientific name) identified at the different locations (1=taxon identified at the location, 0=taxon not identified at the location)

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
102788	Abludomelita obtusata	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
141433	Abra alba	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
411048	Acontiaria	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
100694	Actinia	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
1360	Actiniaria	0	1	0	0	1	0	0	0	0	1	1	1	1	1	1
100986	Actinothoe sphyrodeta	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
140629	Adalaria proxima	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
138709	Aeolidia papillosa	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
137631	Aeolidiella	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
138711	Aeolidiella glauca	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
192	Aeolidiidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
140687	Aequipecten opercularis	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
468026	Alcyonidioides mytili	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
110993	Alcyonidium	1	1	1	0	0	0	0	1	0	1	1	1	0	1	1

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
153730	Alcyonidium condylocinereum	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
111602	Alcyonidium mamillatum	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
111604	Alcyonidium parasiticum	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
125333	Alcyonium digitatum	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1
234851	Alitta virens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
111022	Amathia	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
421139	Amphibalanus improvisus	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0
130869	Amphiglena mediterranea	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
125064	Amphipholis squamata	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
214	Anomiidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
1292	Anthozoa	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0
102012	Aora gracilis	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
101368	Aoridae	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

AphialD	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
148594	Apocorophium lacustre	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
236495	Apolochus neapolitanus	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
111607	Arachnidium fibrosum	1	1	0	0	0	1	1	1	1	0	0	0	0	0	0
129868	Arenicola marina	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
879714	Asbjornsenia pygmaea	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
1839	Ascidiacea	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
103719	Ascidiella scabra	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
111350	Aspidelectra melolontha	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
138818	Astarte borealis	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
123219	Asterias	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
123776	Asterias rubens	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
123080	Asteroidea	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
106875	Atelecyclus	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
107486	Athanas nitescens	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
712167	Austrominius modestus	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0
106057	Balanidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
106122	Balanus	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
106213	Balanus balanus	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1
106215	Balanus crenatus	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
105	Bivalvia	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
145950	Blidingia minima	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
117015	Bougainvillia	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
491633	Brachystomia scalaris	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
146142	Bryozoa	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1
138878	Buccinum undatum	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
1100	Calanoida	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
111196	Callopora dumerilii	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
1606	Campanulariidae	0	0	1	0	1	0	0	0	1	1	1	1	1	1	1
107276	Cancer pagurus	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
129876	Capitella capitata	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
921	Capitellidae	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
101830	Caprella equilibra	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
101839	Caprella linearis	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1
146768	Caprella mutica	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
101361	Caprellidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
106674	Caridea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
141611	Catriona gymnota	1	1	1	1	0	1	0	1	1	0	0	0	0	0	0
111397	Celleporella hyalina	0	1	0	0	1	1	1	1	1	0	0	0	0	0	0
129912	Chaetopterus norvegicus	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
129914	Chaetopterus variopedatus	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
148582	Chelicorophium curvispinum	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
130888	Chone duneri	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
919	Cirratulidae	1	1	1	1	0	0	0	0	0	0	1	0	0	0	1
129243	Cirratulus	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
117368	Clytia hemisphaerica	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
110903	Conopeum	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
111351	Conopeum reticulum	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
1080	Copepoda	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
101489	Corophium	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
138018	Coryphella	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
139987	Coryphella verrucosa	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
107277	Corystes cassivelaunus	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
397383	Crassicorophium crassicorne	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
138963	Crepidula fornicata	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1
141280	Crisilla semistriata	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
834039	Crisularia plumosa	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
129989	Ctenodrilus serratus	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
1248	Ctenophora	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
1137	Cumacea	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
138543	Cuthona	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
1471945	Cylista elegans	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
855674	Cylista troglodytes	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0
855675	Cylista undata	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0
139523	Dendronotus frondosus	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
100872	Diadumene cincta	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
103457	Diplosoma	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
103579	Diplosoma listerianum	1	1	1	1	0	1	1	1	1	0	0	0	0	0	0
131116	Dipolydora caulleryi	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
131119	Dipolydora giardi	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
139604	Donax vittatus	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
9904	Dorididae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
137916	Doto	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
139631	Doto coronata	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
1473658	Duvaucelia plebeia	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
132324	Dysidea fragilis	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
124392	Echinocardium cordatum	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
1806	Echinodermata	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
123082	Echinoidea	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
157933	Ectopleura larynx	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
100730	Edwardsia	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
110904	Electra	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
111354	Electra monostachys	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
111355	Electra pilosa	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
122710	Emplectonema gracile	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
138333	Ensis	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
139718	Epitonium clathratulum	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0
146905	Epitonium clathrus	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
129443	Eteone	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
130616	Eteone longa	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
156083	Eualus cranchii	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
107507	Eualus pusiolus	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
137954	Eubranchus	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0
117093	Eudendrium	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
129445	Eulalia	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
130639	Eulalia viridis	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
130644	Eumida sanguinea	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
130375	Eunereis longissima	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
151894	Euspira nitida	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0
146907	Fabulina fabula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
137997	Facelina	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
139908	Facelina bostoniensis	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1
111652	Farrella repens	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
408266	Fenestrulina delicia	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0
190	Flabellinidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
1410	Foraminifera	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
102275	Gammarus crinicornis	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
101	Gastropoda	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
130749	Gattyana cirrhosa	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
101977	Gitana sarsi	0	1	1	0	0	1	1	1	1	0	0	0	0	0	0
118994	Gnathia maxillaris	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
138831	Goodallia triangularis	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
111984	Gromia	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
165801	Halichondria (Halichondria) bowerbanki	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
165853	Halichondria (Halichondria) panicea	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0
129491	Harmothoe	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
130754	Harmothoe antilopes	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
130760	Harmothoe clavigera	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
130762	Harmothoe extenuata	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
130763	Harmothoe fragilis	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
130769	Harmothoe imbricata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
130770	Harmothoe impar	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
1102	Harpacticoida	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
946	Hesionidae	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1
138749	Heteranomia squamula	1	1	1	1	0	1	1	1	1	0	1	1	0	0	1
140103	Hiatella arctica	0	0	0	0	0	1	0	0	1	0	1	1	0	1	1
107518	Hippolyte varians	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
106777	Hippolytidae	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
107253	Homarus gammarus	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
117644	Hydractinia echinata	1	1	1	1	0	1	1	1	1	0	1	1	0	0	1
117890	Hydrallmania falcata	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
1337	Hydrozoa	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
152250	Hypereteone foliosa	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
103251	Hyperia galba	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
118454	Idotea	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
119044	Idotea granulosa	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
119050	Idotea pelagica	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
102346	Iphimedia nexa	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
101571	Jassa	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
102432	Jassa herdmani	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
102433	Jassa marmorata	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
140161	Kellia suborbicularis	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
345281	Kurtiella bidentata	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
152367	Lagis koreni	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0
131495	Lanice conchilega	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1
117382	Laomedea flexuosa	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0
101469	Lembos	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
130801	Lepidonotus squamatus	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1
142827	Leptoplana tremellaris	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0
13552	Leptothecata	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
131715	Leucosolenia	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0
132219	Leucosolenia complicata	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
132233	Leucosolenia variabilis	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
122314	Lineidae	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
106925	Liocarcinus	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
107387	Liocarcinus depurator	0	0	0	0	1	0	0	0	0	0	1	1	1	0	1
107388	Liocarcinus holsatus	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0
107390	Liocarcinus marmoreus	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
107392	Liocarcinus navigator	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
878470	Macomangulus tenuis	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
205077	Macropodia	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
107345	Macropodia rostrata	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
836033	Magallana gigas	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
131131	Malacoceros fuliginosus	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
923	Maldanidae	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
152304	Malmgrenia ljungmani	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
130075	Marphysa sanguinea	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
149682	Megabalanus coccopoma	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
102840	Melita hergensis	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
120072	Mesopodopsis slabberi	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
103116	Metopa alderi	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
100982	Metridium senile	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
111421	Microporella ciliata	0	1	0	0	0	1	1	1	1	0	0	0	0	0	0
101561	Microprotopus	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
103776	Molgula complanata	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
103448	Molgulidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
148591	Monocorophium	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
225814	Monocorophium acherusicum	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
148592	Monocorophium insidiosum	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
148603	Monocorophium sextonae	1	0	0	0	1	1	1	1	1	0	0	0	0	0	0
506128	Musculus subpictus	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1
129659	Myrianida	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0
238194	Myrianida edwarsi	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
140480	Mytilus edulis	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
107398	Necora puber	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0
799	Nematoda	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
152391	Nemertea	0	0	1	1	1	1	0	1	0	1	1	1	0	1	1
117195	Nemertesia	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
117809	Nemertesia antennina	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
131504	Neoamphitrite figulus	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
136060	Nephasoma (Nephasoma) minutum	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
22496	Nereididae	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1
130185	Nereimyra punctata	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
129379	Nereis	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
130404	Nereis pelagica	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1
130407	Nereis zonata	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
488966	Nototropis swammerdamei	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1
1762	Nudibranchia	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1
117034	Obelia	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
117386	Obelia dichotoma	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
117389	Obelia longissima	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0
141022	Odostomia turrita	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
122817	Oerstedia dorsalis	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
175	Onchidorididae	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
138288	Onchidoris	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
150457	Onchidoris bilamellata	1	0	1	0	0	0	1	1	1	0	0	0	0	0	0
140640	Onchidoris muricata	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
125131	Ophiothrix fragilis	1	1	1	1	0	1	0	1	0	0	0	0	0	0	0
123574	Ophiura	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0
124913	Ophiura albida	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
123200	Ophiuridae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
123084	Ophiuroidea	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
140658	Ostrea edulis	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
215	Ostreidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
710680	Oxydromus flexuosus	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
107232	Pagurus bernhardus	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0
111808	Pedicellina nutans	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
535477	Perforatus perforatus	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
140737	Phaxas pellucidus	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
130601	Pholoe inornata	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
134741	Phoxichilidium femoratum	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
101864	Phtisica marina	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
334506	Phyllodoce groenlandica	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
130670	Phyllodoce laminosa	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
130673	Phyllodoce longipes	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
334510	Phyllodoce maculata	1	1	1	0	0	1	0	1	0	0	0	0	0	0	0
334512	Phyllodoce mucosa	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
931	Phyllodocidae	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
107418	Pilumnus hirtellus	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1
107473	Pinnotheres pisum	0	0	1	0	1	1	0	0	1	0	0	0	0	0	0
107188	Pisidia longicornis	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1
117824	Plumularia setacea	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1091	Podocopida	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
147109	Polinices	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
138369	Polycera	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
140838	Polycera quadrilineata	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1
883	Polychaeta	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
2853	Polycladida	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
131141	Polydora ciliata	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1
131143	Polydora cornuta	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
939	Polynoidae	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0
558	Porifera	0	0	0	0	1	1	0	0	0	1	1	1	1	0	0
130954	Potamilla neglecta	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
145800	Prasiola stipitata	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
102	Prosobranchia	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
152248	Psamathe	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
152249	Psamathe fusca	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
124319	Psammechinus miliaris	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
110427	Pseudocuma	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
110627	Pseudocuma (Pseudocuma) longicorne	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
141334	Pusillina inconspicua	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
836215	Pyrgiscus jeffreysii	0	1	0	1	0	1	1	1	1	0	0	0	0	0	0
123	Rissoidae	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
129520	Sabellaria	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
130867	Sabellaria spinulosa	1	1	1	1	0	0	0	1	0	1	0	0	0	0	0
985	Sabellidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
100681	Sagartiidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
117491	Sarsia tubulosa	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
862795	Schizomavella (Schizomavella) linearis	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
110976	Scruparia	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
111539	Scruparia ambigua	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
106210	Semibalanus balanoides	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
411720	Seraphsidae	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
117913	Sertularia cupressina	0	1	1	0	0	0	0	0	0	1	1	0	0	1	0
396735	Smittoidea prolifica	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
140432	Sphenia binghami	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
913	Spionidae	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
555935	Spirobranchus triqueter	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1
989	Spirorbinae	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
334842	Spirorbis (Spirorbis) spirorbis	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
101770	Stenothoe	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0
103166	Stenothoe marina	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1
103169	Stenothoe monoculoides	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
103174	Stenothoe tergestina	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
103175	Stenothoe valida	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
124321	Strongylocentrotus droebachiensis	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
132251	Sycon ciliatum	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
948	Syllidae	1	1	1	1	0	0	0	0	0	1	0	1	0	0	1
131435	Syllis gracilis	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
131452	Syllis prolifera	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
118154	Telmatogeton japonicus	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1
982	Terebellidae	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
194	Tergipedidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
141641	Tergipes tergipes	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
234208	Testudinalia testudinalis	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
131543	Thelepus cincinnatus	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
131544	Thelepus setosus	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
152378	Thracia phaseolina	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1

AphiaID	Scientific Name	Location														
		BW2	BW8	CP5	CP6	FINO	PA1	PA20	PA45	PA60	HR33	HR55	HR58	HR91	HR92	HR95
876825	Tritia incrassata	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
1391526	Tritia varicosa	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1
138580	Tritonia	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
138582	Trivia	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
141744	Trivia monacha	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
117258	Tubularia	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
117994	Tubularia indivisa	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1603	Tubulariidae	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
146420	Tunicata	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
144296	Ulva	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
234471	Ulva intestinalis	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
234474	Ulva linza	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
100706	Urticina	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
100834	Urticina felina	1	0	1	0	0	1	1	1	1	0	0	0	0	0	0
181364	Venerupis corrugata	0	1	1	1	0	1	1	0	1	0	0	0	0	0	1
106257	Verruca stroemia	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

VIII Assessment of sustainable strategies for offshore wind farm decommissioning and Discussion

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4 Assessment of sustainable strategies for offshore wind farm decommissioning

The assessment of sustainable strategies for offshore wind-farm decommissioning is a complex procedure that is outlined in this chapter. In order to assess sustainability, decision criteria consisting of objectives that define sustainable offshore wind farm decommissioning as well as attributes that allow for measuring the achievement of the objectives need to be defined for the three pillars of sustainability (see chapter 4.1). To be able to assess decommissioning strategies, in-depth knowledge of the decommissioning processes is required (see chapter 4.2 and 4.4) and decommissioning scenarios need to be constructed (see chapter 4.3). Once this knowledge base is established, the attributes of the decision criteria are calculated and analysed individually (see chapter 4.5). A final multi criteria decision analysis enables the assessment of the decommissioning scenarios while considering all the decision criteria (see chapter 4.6).

4.1 Objectives for sustainable offshore wind farm decommissioning

In order to realise sustainable offshore wind-farm decommissioning, economic, environmental and social objectives need to be defined. In the social category, within the research project *SeeOff* the focus is laid upon ‘health and safety’. For a comprehensive structure, the three categories **economy**, **environment** and **health and safety** were split up into various aspects. For each aspect, decision criteria were formulated. Decision criteria consist of objectives and attributes that measure the achievement of the objectives. Within the research project *SeeOff*, five objectives for sustainable offshore wind farm decommissioning were discussed and defined at a workshop with stakeholders (Figure 62):

→ OWF decommissioning is **economically efficient**.

→ OWF decommissioning is associated with **low GHG emissions**.

→ OWF decommissioning has **minor impact on local biodiversity**.

→ OWF decommissioning is has **high resource efficiency**.

→ OWF decommissioning is associated with **few hazards**.

Sustainable decommissioning of offshore wind farms					
Category	**Economy**	**Environment**			**Health and safety**
Aspect	Economic efficiency	GHG-Emission	Biodiversity	Resource efficiency	Safety at work
Objective	Economic efficiency	Low GHG-Emission	Minor local impact	High resource efficiency	Few hazards
Attribute	(Present) value of costs/ decommis-sioned MW	CO_2-Equivalent	Fraction of species richness maintained	Recovery rate	Hazard measure

Figure 62: *SeeOff* objective hierarchy for sustainable offshore wind farm decommissioning, including categories, aspects, objectives and attributes.

4.1.2 Environment

4.1.2.1 Greenhouse gas emissions

According to the German Federal Climate Change Act (Bundes-Klimaschutzgesetz (KSG)) greenhouse gas emissions are to be reduced by at least 65 % by 2030 compared to 1990. The expansion of renewable energies is of great importance here. According to § 1 WindSeeG (2021), offshore wind energy is to be expanded to 20 GW by 2030 and 40 GW by 2040. The coalition agreement of the new German government announces an increase in offshore expansion targets to 30 GW by 2030, 40 GW by 2035 and 70 GW by 2045 (SPD, GRUENE, FDP 2021). In offshore wind energy, the largest share of greenhouse gas emissions can be traced back to vessel transport (Wagner et al. 2011).

According to the IMO Strategy on reduction of GHG emissions from vessels (MEPC 2018), CO_2 emissions per transport service are to be reduced by 40 % by 2030 and by 70 % by 2050 compared to 2008. Short-term measures include improving the energy efficiency design index (EEDI) and Vessel Energy Efficiency Management Plans (SEEMP), optimising and reducing speed, using renewable energies and optimising the logistics chain and its planning.

EnBW Energie Baden-Württemberg AG wants to reduce 50 % of CO_2 emissions by 2030 compared to 2018 and to be climate neutral regarding their own emissions by 2035 (EnBW AG 2020). Vattenfall intends to be on track to achieve the 1.5° C target by 2030, based on science-based target assessment

(Vattenfall 2020). TenneT aims to be climate-neutral by 2025 (TenneT Holding B.V. 2019). Suppliers and service providers are also paying more attention to reducing greenhouse gas emissions.

Within the framework of the *SeeOff* research project, it was thus defined as a goal that dismantling should be accompanied under consideration of low greenhouse gas emissions. To measure the achievement of the goal, the internationally recognised attribute CO_2 equivalents is used.

Table 32: Objective profile 'Greenhouse gas emissions'

Category	Environment
Aspect	**Greenhouse gas emissions**
Objective	**OWF decommissioning is associated with low greenhouse gas emissions.**
Explanation	The reduction of greenhouse gas emissions is of great importance internationally and nationally, as well as for companies in the offshore wind energy industry. Deconstruction strategies that go hand in hand with low greenhouse gas emissions are therefore of outstanding relevance.
Contribution to national / international goals	**Sustainable Development Goal 13**. Take urgent action to combat climate change and its impacts **Climate protection target 1 of the** United Nations **Paris Agreement** (UN 2015b) is to limit the increase in the average temperature of the Earth to well below 2°C above pre-industrial levels (long-term temperature goal). **Goals of the German** Federal Climate Change Act (Bundes-Klimaschutzgesetz (KSG)) on the reduction of greenhouse gas emissions
Attribute	CO_2-Equivalents
Unit	t CO_{2}-Equivalents

4.1.2.2 Biodiversity

The conservation of biological diversity is of great importance at national and international level. The United Nations Convention on Biological Diversity aims at 'the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, in particular through appropriate access to genetic resources and appropriate transfer of relevant technologies, taking into account all rights over such resources and technologies, and through appropriate funding' (UN 1992). The Strategic Plan for Biodiversity 2011-2020 pursues the aim that 'by 2050, biodiversity is valued, protected and restored' (UN 2010).

At national level, § 1 para. 1 BNatSchG regulates the permanent safeguarding of biological diversity through the protection of nature and landscape. Descriptor 1 of EU Directive 2008/56/EC (transposed into national law by the Marine Strategy Framework Directive Implementation Act) specifies that "the quality and occurrence of habitats and the distribution and abundance of species correspond to prevailing physiographic, geographic and climatic conditions."

The introduction of hard substrates and the fishing ban within the OWF has led to a change in biodiversity. By taking appropriate measures (e.g., maintaining scour protection layer (SPL) or parts of FOU), OWF decommissioning can thus influence local biodiversity.

Within the *SeeOff* research project, the goal was thus defined that OWF decommissioning should be accompanied by a low impact on local biodiversity. For this purpose, the attribute 'species richness' is applied.

Table 33: Objective profile 'Biodiversity'

Category	Environment
Aspect	**Biodiversity**
Objective	**The OWF decommissioning is associated with a minor impact on local species richness**
Explanation	Safeguarding biodiversity is a goal that is both internationally important (e.g. in the UN Convention on Biological Diversity or the Marine Strategy Framework Directive 2008/56/EC) and anchored in national law (e.g. in the Federal Nature Conservation Act). (UN 1992) or Marine Strategy Framework Directive 2008/56/EC) as well as being enshrined in national law (e.g., in the BNatSchG). Due to the artificial reef effect of the foundation structures, OWF contribute to the change in biodiversity (Dannheim et al. 2020).
Contribution to national / international goals	**Strategic objective of the Strategic Plan for Biodiversity B**. Reduce pressures directly affecting biodiversity and promote sustainable use **Strategic objective of the Strategic Plan for Biodiversity C**: Improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity **Target 6 of the European Biodiversity Strategy 2020**: Increase the EU's contribution to averting global biodiversity loss. **Environmental Objective 3 under the Marine Strategy Framework Directive**: Keep seas free from degradation of marine species and habitats due to the impact of human activities
Attribute	Fraction of species richness maintained

4.1.2.3 Resource efficiency

Within the framework of the German Resource Efficiency Programme, the goal was set to make the extraction and use of natural resources more sustainable and to reduce the associated environmental impacts as far as possible (BMUB 2015). The focus here is on increasing resource efficiency and resource conservation in the use of abiotic raw materials, which are not primarily used for energy production, and biotic raw materials, insofar as they are used for material purposes (BMUB 2015).

In improving material and resource efficiency, avoiding waste and increasing reuse and recycling are of great importance. According to Article 4 Waste Framework Directive (EU DIRECTIVE 2008/98/EC) and § 6 Abs1 KrWG, the measures of prevention and waste management are in the following sequence

1. Prevention
2. Preparing for re-use
3. Recycling
4. Other recovery, in particular energy recovery and backfilling
5. Disposal

By definition of § 3 para. 1 KrWG, waste is 'any substance or object which its holder discards, intends to discard or is required to discard', so that prevention and preparation for re-use do not apply to waste.

In 2011, the Member States of the European Commission set a target to reuse, recycle or recover 70 % of all construction and demolition waste (EU Directive 2008/98/EC). In 2018, the recycling rate of construction and demolition waste across Europe was already 88 % (including backfilling) (Statistisches Bundesamt 2018).

The *SeeOff* research project has defined as a goal that OWF decommissioning is accompanied by high resource efficiency. The achievement of the goal is measured with the attribute recycling rate.

Table 34: Objective profile 'resource efficiency'

Category	Environment
Aspect	**Resource efficiency**
Objective	**OWF dismantling goes hand in hand with a high recycling rate**
Explanation	Increasing resource efficiency is of great importance nationally and internationally. The recycling of waste makes a significant contribution to increasing resource efficiency.
Contribution to national / international goals	**Sustainable Development Goal 12**. Ensuring Sustainable Consumption and Production Patterns **EU Action Plan** (2015) **objective**: preserving the value of products, materials and resources within the economy for as long as possible and generating as little waste as possible is an essential contribution to the EU's efforts to achieve a sustainable, low-carbon$_2$, resource-efficient and competitive economy **German Resource Efficiency Programme Goals Raw materials**: increasing resource efficiency
Attribute	Recovery rate
Unit	%

4.2 Assessment approach

For the determination of sustainable decommissioning strategies, a process-based approach is applied:

1. Compilation of decommissioning processes
2. Criteria-based selection of decommissioning processes
3. Documentation and parametrization of decommissioning processes
4. Compilation of decommissioning scenarios
5. Calculation of sustainability attributes
6. Multi criteria decision analysis

1. Compilation of decommissioning processes

Decommissioning processes are compiled and structured (Figure). First, three main processes are defined: dismantling offshore, dismantling and comminution on land as well as recovery and disposal. Offshore dismantling is broken down to decommissioning processes according to the OWF components that are dismantled: WTG, WTG-FOU, OSS topside, OSS-FOU, sea cables and SPL. Dismantling and comminution ashore and is subdivided accordingly, except that the WTG components are considered individually. Unlike the offshore and onshore dismantling processes, where the focus lies upon the inputs, the OWF components and their recovery and disposal processes are structured according to the output, the secondary materials and secondary fuels.

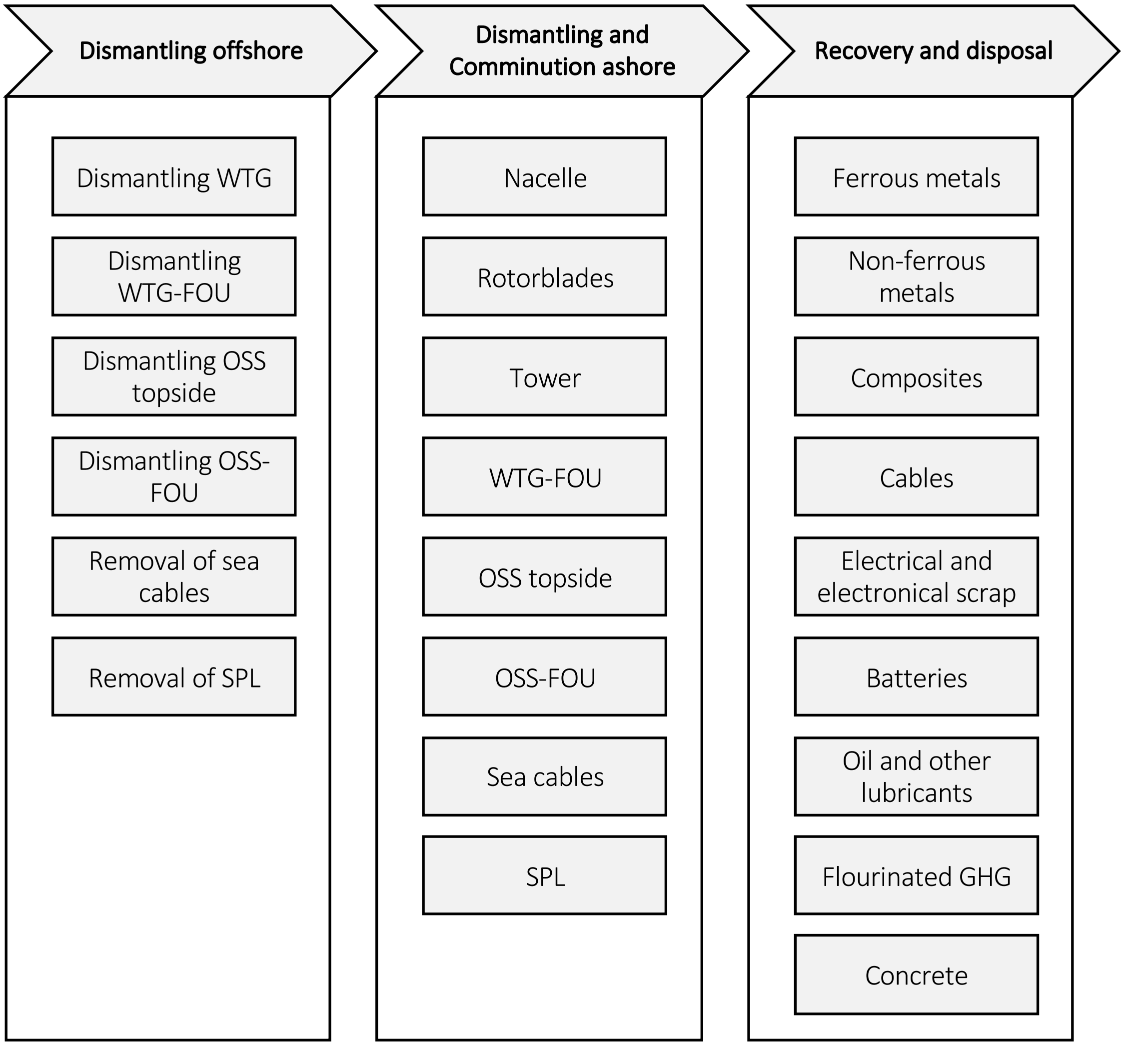

Figure 63: Overview of decommissioning processes

In order to select decommissioning processes for further analysis, first different process options are collected. For instance, there are different techniques for dismantling WTG-FOU offshore, such as Abrasive Water Jetting (AWJ), vibratory or overpressure extraction (see chapter 3.3.1).

2. Criteria-based selection of decommissioning processes

As an in-depth analysis of all possible decommissioning processes is not feasible, process options are selected based on exclusion and selection criteria (Table 36). Availability of data and information is a basic requirement for further analysis and therefore the central criterion to exclude processes for further analysis. This also affects all processes that are not state of the art in technology. For the offshore dismantling of WTG-FOU, this means that techniques like overpressure extraction or hydraulic presses and floating panels, were not taken into consideration for further analysis. For the continued selection of processes, criteria for the categories of environment, economic and social are defined and applied.

Table 36: Criteria for the exclusion and selection of process options (Spielmann et al. 2021)

	Category	Criteria	Explanation for selection and exclusion of process options
Exclusion criteria	General	Availability of data and information	▪ Data and information are not sufficiently available
Selection criteria	Environment	GHG-emissions	▪ Different amounts of GHG are emitted
		Recycling	▪ Variation in amount of recycled material ▪ Influence on materials flow
		Benthos	▪ Influence on the conservation interest of benthos
	Economic	Economic efficiency	▪ Associated to relevant costs ▪ Variation in resource inputs (type and duration)
	Social	Accidents	▪ Number of accidents (after (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 2020))
		Hazards	▪ Variation in degree of potential of hazards ▪ Long-lasting exposure to hazard ▪ Hazards resulting in severe consequences ▪ Multiple, simultaneous hazards

3. Documentation and parametrization of decommissioning processes

The decommissioning processes are documented and parametrized according to the depth required for the subsequent calculation of the sustainability attributes. First, general procedures of the processes and required resources (e.g., vessels, cranes or SPMT) are documented (see chapter 3.5). Next, the processes are parametrized and data is collected as required for the attributes. For example, to calculate decommissioning costs, the entire charter duration of the vessel is of relevance, whereas for the estimation of GHG emissions, the actual durations for operation and transit of the vessel are of interest. For estimating the level of hazards, a much greater level of detail is required and durations of individual activities need to be collected (Figure 64).

In the case of OWF decommissioning, there is only scarce experience and little is known about the actual processes. Therefore, all information and data collected are based on statements and estimates of experts and literature research or derived from the construction or operational phase of offshore wind farms. For many processes this is a challenging task. For instance, when feeder concepts were discussed with different experts, opinions on the feasibility and safety differed widely (Wittek 2021), (van de Brug 2021). Moreover, the more detailed some of the processes are investigated, the more uncertainties are revealed: for example, in the estimation of process and activity durations as well as the identification of all hazard factors that can be present. See chapter 4.5 for more information on the data collection for the individual attributes. To the best of the authors' knowledge, all available information and data for the documentation and parametrization of the decommissioning processes and for the calculation of the decision criteria were collected.

4. Compilation of decommissioning scenarios

The different process options were combined to decommissioning scenarios. In the research project *SeeOff,* one baseline scenario and nine alternative scenarios are described. The scenarios differ in dismantling technologies, logistics and scope of decommissioning. For a detailed list of decommissioning scenarios, see chapter 4.3.

5. Calculation of sustainability attributes

The sustainability attributes are calculated for the different decommissioning scenarios. See chapter 4.5 for detailed information on the calculation of the individual attributes.

6. Multi criteria decision analysis

In order to assess the sustainability of the decommissioning scenarios the different criteria need to be considered together. Multi criteria decision making (MCDA) supports decision making under consideration of multiple objectives and is hence a suitable tool. From the variety of MCDA methods, the weighted sum model (WSM) is chosen. This method incorporates the weighting of criteria with priority analysis, the assessment of the decommissioning scenarios as well as the calculation and interpretation of the decision scores.

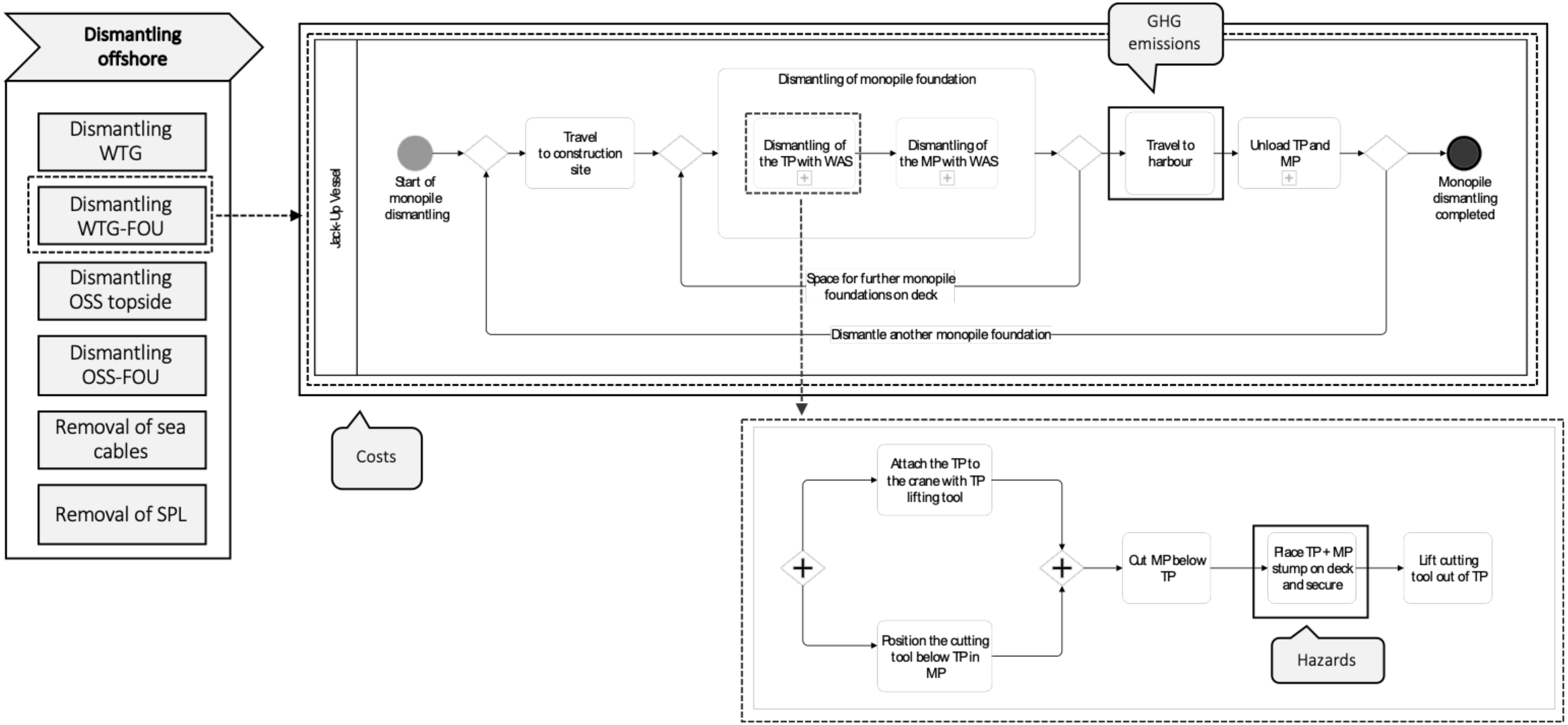

Figure 64: Excerpt of an exemplary documentation and parametrization of the process of offshore dismantling of wind turbine generator foundation (WTG-FOU)

4.3 Decommissioning scenarios

The decommissioning processes incl. process options described in chapter 3.5 are combined to decommissioning scenarios. A total of ten decommissioning scenarios are analysed: one baseline scenario and nine alternative decommissioning scenarios (Table 37).

Baseline scenario

In the baseline scenario, it is assumed that dismantling is carried out largely in reverse order to the construction. For offshore dismantling, jack-up vessels (JUV) or crane vessels are utilised. Vessels operate in shuttle mode, where the vessel involved in the actual dismantling also transports the components to the harbour where they are unloaded with the help of the vessel's crane. The FOU of the WTG and OSS is cut 1 m below the seabed using the AWJ method. For the WTG, the first cut is made below the TP. The SPL and sea cables will also be removed.

Scenario 1 (S1): Feeder concept WTG

In this scenario, the WTG is also dismantled by a JUV, but the components are transported to the harbour by means of a feeder concept with help of deck carriers and the components are unloaded ashore with a crane (see chapter 3.5.1.1).

Scenario 2 (S2): Feeder concept WTG-FOU

The WTG-FOU are dismantled by the JUV in the same way as in the baseline scenario, but in the feeder concept they are transported to the harbour by deck carriers and are unloaded ashore by crane (see chapter 3.5.1.3).

Scenario 3 (S3): Feeder concept: WTG and WTG-FOU

In this scenario the transport of the WTG and WTG-FOU is carried out with feeder concepts as outlined in scenarios S1 and S2 (see chapter 3.5.1.1 and 3.5.1.3).

Scenario 4 (S4): Load-off OSS with SPMT

As in the baseline scenario, the OSS is dismantled by a crane vessel and the topside and jacket are transported by a North Sea barge. In this scenario, however, the components are not unloaded with the help of the crane vessel, but by means of SPMT. The crane vessel thus does not have to return to the reference harbour (see chapter 3.5.1.3).

Scenario 5 (S5): SPL left in situ

In contrast to the baseline scenario, the SPL is not removed in this scenario, but remains in the construction field.

Scenario 6 (S6): Sea cables remain in situ

In this scenario the IAC and export cables are not removed. The cables are cut outside the SPL and the cable ends are buried into the seabed (see chapter 3.5.1.2).

Scenario 7 (S7): WTG-FOU: cut 3 m above seabed

In this scenario, the WTG are cut 3 m above seabed and removed, leaving part of the WTG-FOU above the seabed. The SPL is also not removed in this scenario (see chapter 3.5.1.3).

Scenario 8 (S8): WTG-FOU: complete removal

The WTG-FOU are removed completely with help of vibratory extraction in this scenario (see chapter 3.5.1.3).

Scenario 9 (S9): Cut with diamond wire cutting machine

In this scenario the WTG-FOU and OSS-FOU are not cut with WAS, but with diamond wire cutting machine (see chapter 3.5.1.3).

Table 37: Overview of decommissioning scenarios incl. process options (WTG = wind turbine generator, FOU = foundation, OSS = offshore substation, SPL = scour protection layer, AWJ = Abrasive water jetting, SPMT = Self-propelled modular transporter)

Decommissioning scenario		WTG	WTG-FOU			OSS		SPL	Sea cables
		Transport	Scope of decom-missioning	Decom-missioning technology	Transport	Decom-missioning technology	Load-off at harbour	Scope of decom-missioning	Scope of decom-missioning
BS	Baseline scenario	Shuttle concept	Cut 1 m below seabed	AWJ	Shuttle concept	AWJ	Crane vessel	Removal	Removal
S1	Feeder concept: WTG	Feeder concept	Cut 1 m below seabed	AWJ	Shuttle concept	AWJ	Crane vessel	Removal	Removal
S2	Feeder concept: WTG-FOU	Shuttle concept	Cut 1 m below seabed	AWJ	Feeder concept	AWJ	Crane vessel	Removal	Removal
S3	Feeder concept: WTG und WTG-FOU	Feeder concept	Cut 1 m below seabed	AWJ	Feeder concept	AWJ	Crane vessel	Removal	Removal
S4	Load-off OSS with SPMT	Shuttle concept	Cut 1 m below seabed	AWJ	Shuttle concept	AWJ	Roll-off with SPMT	Removal	Removal
S5	SPL left in situ	Shuttle concept	Cut 1 m below seabed	AWJ	Shuttle concept	AWJ	Crane vessel	Left in situ	Removal
S6	Sea cables left in situ	Shuttle concept	Cut 1 m below seabed	AWJ	Shuttle concept	AWJ	Crane vessel	Removal	Left in situ
S7	WTG-FOU: Cut above seabed	Shuttle concept	Cut 3 m above seabed	AWJ	Shuttle concept	AWJ	Crane vessel	Left in situ	Removal
S8	WTG-FOU: Complete removal	Shuttle concept	Complete removal	AWJ -/ Vibratory extraction	Shuttle concept	AWJ	Crane vessel	Removal	Removal
S9	FOU: Cut with diamond wire saw	Shuttle concept	Cut 1 m below seabed	Diamond wire cutting machine	Shuttle concept	Diamond wire cutting machine	Crane vessel	Removal	Removal

4.5 Decision criteria

In this chapter, the calculation and interpretation of the results of the decision criteria for sustainable decommissioning of offshore wind farms are elaborated.

4.5.2 Greenhouse gas emissions

One of the objectives defined within the research project *SeeOff* states that OWF decommissioning is associated with low GHG emissions. CO_2-equivalents is an appropriate attribute to measure GHG-emissions.

In OWF decommissioning GHG emissions can be traced to fuel-consuming activities; namely those associated with vessels, resources required for disassembling OWF components and transporting them onshore. Hence, GHG emissions for those activities were determined and CO_2-equivalents calculated.

4.5.2.1 Calculation of GHG-Emissions

GHG emissions in terms of CO_2-equivalents are calculated as a function of the duration of the fuel consuming activity (*a*) in h (t_a), the fuel consumption of the resources (*r*) in l/h, t/h and kWh (fc_r), conversion factors in kg CO_2-equivaltents for the pollutants CO_2, CH_4 and N_2O (*i*) in kg/l, kg/t and kg/kWh (*cf*), the number of repetitions of the activity (rep_a) and the number of resources (n_r) (Table 47). Minimal, average and maximal durations of the fuel consuming activities are determined and are the basis for the calculation of minimal, average and maximal CO_2-Equivalents.

$$CO_2 Equivalents = \sum_r \left(n_r \cdot fc_r \sum_a \left(t_a \cdot rep_a \sum_i cf_i \right) \right) \quad \text{[equation 2]}$$

Table 47: Terms and explanation of the variables used to calculate CO2-equivalents

Term	Explanation
t_a	Duration (*t*) of the activity (*a*) in h
fc_r	Fuel consumption (*fc*) of the resource (*r*) in l/h, t/h and kWh
cf_i	Conversion factor (*cf*) in kg CO_2-Equivalents for the pollutants CO_2, CH_4 and N_2O (*i*) in kg/l, kg/t and kg/kWh
rep_a	Number of repetitions of the activity (*a*)
n_r	Amount (*n*) of resources

The duration of the fuel-consuming activities, number of repetitions of these activities and number of resources required for the activities are collected as part of the process analysis by expert interviews and literature research.

The vessel fuel consumptions for transit are calculated based on the vessel specific propulsion power, the loading (design displacement) and the transition speed. A sea margin of 15 % (e.g., due to weather) and a specific fuel consumption of 220 g/kWh are assumed for all vessels. Further it is assumed, that the fuel consumption for jacking amounts to 80 % of the fuel consumption for transit, 50 % for operation and 25 % for standby. All vessels are considered to run on Marine Gas Oil (MGO).

For onshore processes two different approaches are applied:

1) The activity-based approach considering estimates of the duration of fuel consuming activity.
2) The resource throughput approach calculating durations based on the throughput of the fuel consuming resource.

Fuel consumptions were assessed for all resources in operation mode. Two different fuel types were considered: diesel powering most of the onshore resources and the German electricity mix (2019) powering onshore plants.

The conversion factors for the pollutants CO_2, CH_4 and N_2O of the different fuel types are given in Table . Conversion factors of Marine Gas Oil were taken from the UK Government Conversion Factors for Greenhouse Gas (GHG) reporting (UK Government Department for Business, Energy & Industrial Strategy 2021). The conversion factors of diesel derive from the Common Reporting Format (CRF) tables of the German GHG inventory (UBA 2021). These conversion factors are given in kg/TJ and were transformed to kg/l according to the Transport Emission Model (TREMOD) (Allekotte et al. 2020). The conversion factors for the German electricity mix derive from the German Federal Environment Agency (Juhrich 2021). All conversion factors correspond the reference year 2019.

Table 48: Conversion factors in kg CO2-Equivalents for CO2, CH4 and N2O of Marine Gas Oil, diesel and the German electricity mix

Fuel Type	Conversion factors			Reference
	CO_2	CH_4	N_20	
Marine Gas Oil	3 205.99 kg/t	0.82 kg/t	43.27 kg/t	(UK Government Department for Business, Energy & Industrial Strategy 2019)
Diesel	2.641735 kg/l	0.000004 kg/l	0.000143 kg/l	Calculated based on (UBA 2021)
German electricity mix	0.408000 kg/kWh	0.000183 kg/kWh	0.000373 kg/kWh	(Juhrich 2021)

4.5.2.2 CO_2-equivalents in the decommissioning scenarios

CO_2-equivalents differed for the decommissioning scenarios. *S3 Feeder concept: WTG and WTG-FOU* with on average 52 903 t and *S2 Feeder concept: WTG-FOU* with on average 52 164 t had the highest CO_2-equivalents. *S8 WTG-FOU: complete removal* with on average 40 712 t, *S5 SPL left in situ* with on average 40 556 t and *S7 WTG-FOU: Cut above seabed* with on average 41 194 t had the lowest (Table 49, Figure 76).

The range of minimal and maximal CO_2-equivalents (approx. ± 6 200 t) for scenario *S9 FOU: Cut with DWCM* is small compared to all other scenarios. This can be deduced from the fact, that the duration of the cutting activities incl. pre- and post-processing are associated with greater uncertainties than cutting with a DWCM.

Table 49: CO_2-equivaltents per decommissioning scenario

		CO_2-equivalents in t		
	Decommissioning scenarios	Minimal	Mean	Maximal
BS	Baseline scenario	33 775 t	43 860 t	54 485 t
S1	Feeder concept: WTG	33 762 t	44 599 t	57 816 t
S2	Feeder concept: WTG-FOU	38 728 t	52 164 t	67 618 t
S3	Feeder concept: WTG und WTG-FOU	38 715 t	52 903 t	70 949 t
S4	Load-off OSS with SPMT	33 765 t	43 847 t	54 470 t
S5	SPL left in situ	30 833 t	40 556 t	50 817 t
S6	Sea cables left in situ	34 564 t	44 661 t	55 297 t
S7	WTG-FOU: Cut above seabed	31 378 t	41 194 t	51 945 t
S8	WTG-FOU: complete removal	29 571 t	40 712 t	52 100 t
S9	FOU: Cut with diamond wire saw	38 032 t	44 235 t	50 451 t

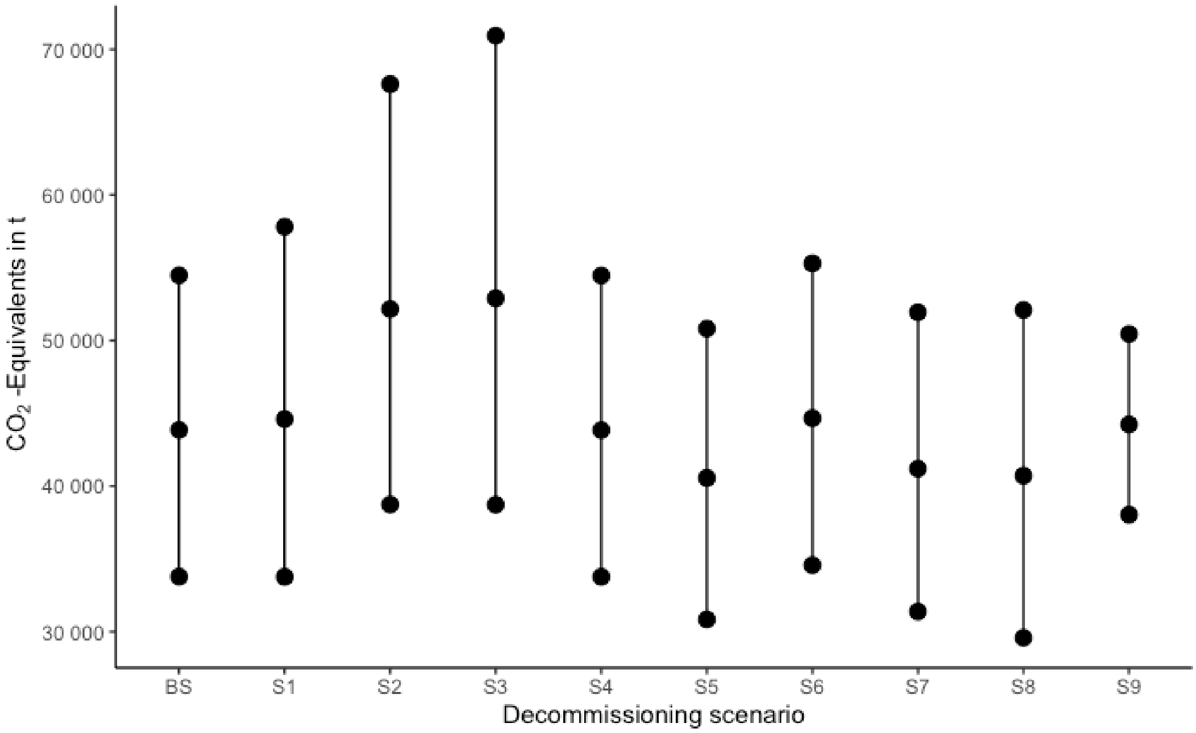

Figure 76: CO_2-Equivalents (minimal, mean and maximal values) per decommissioning scenario (BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM)

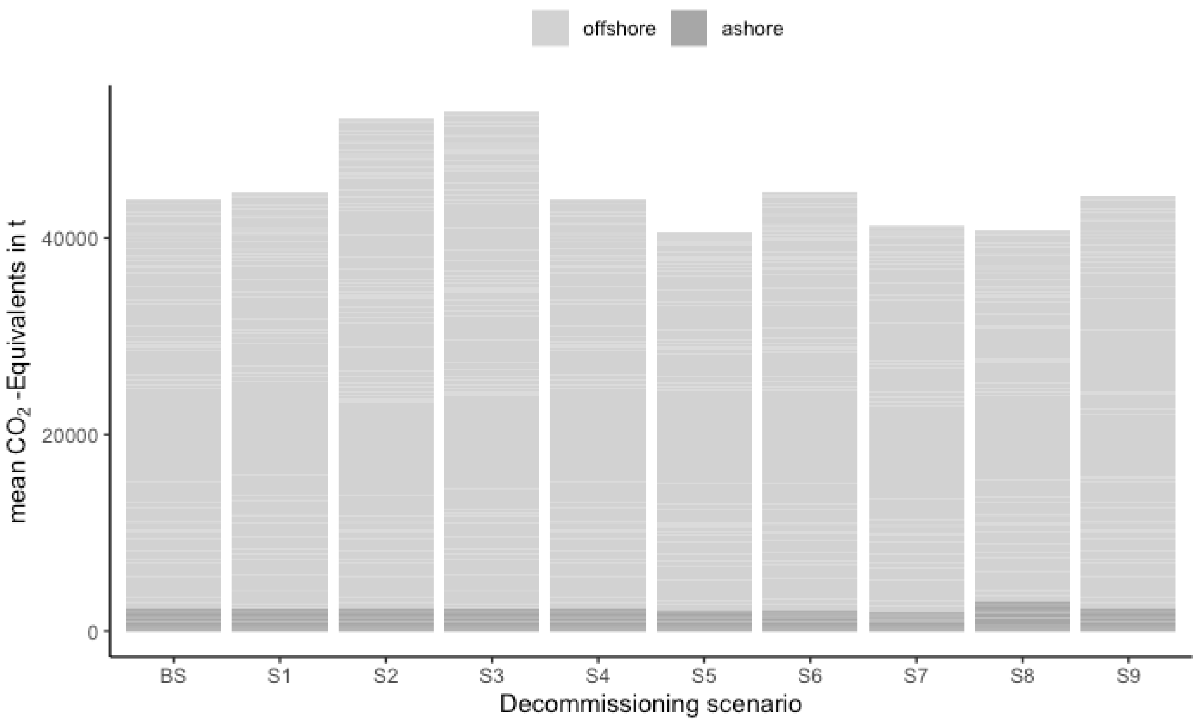

Figure 77: mean CO_2-equivaltents offshore and ashore per decommissioning scenario (BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM)

When compared to offshore processes, CO_2-equivalents of the onshore processes can be neglected; they make up only approx. 4 to 7.5 % of the CO_2-equivalents (Figure 77). Vessel type and spread contribute most to the variation within the decommissioning scenarios (Figure 78 and Figure 79). WTG-FOU decommissioning processes and their associated vessels make up most of the CO_2-equivalents in each scenario. Dismantling activities of the WTG-FOU take a long time (see campaign planning in chapter 4.4.1) and vessels are operated for the according durations, which results in high fuel consumptions and consequently high GHG emissions. Figure 79 also shows the contribution of the feeder concept to the CO_2-equivalents in scenarios *S1= Feeder concept: WTG*, *S2= Feeder concept: WTG-FOU* and *S3= Feeder concept*. The additional use of Deck Carriers for the transport of the WTG components leads to increased GHG emissions.

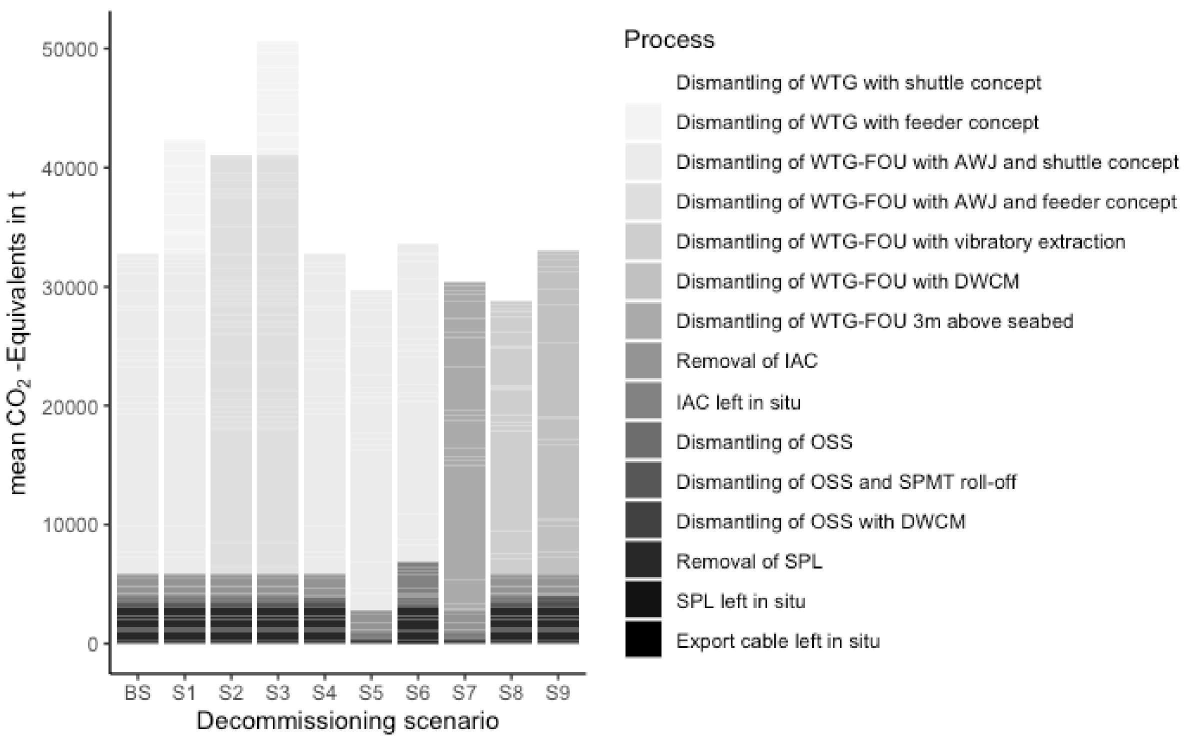

Figure 78: Mean CO_2-equivalents per decommissioning scenario for decommissioning processes offshore(BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM)

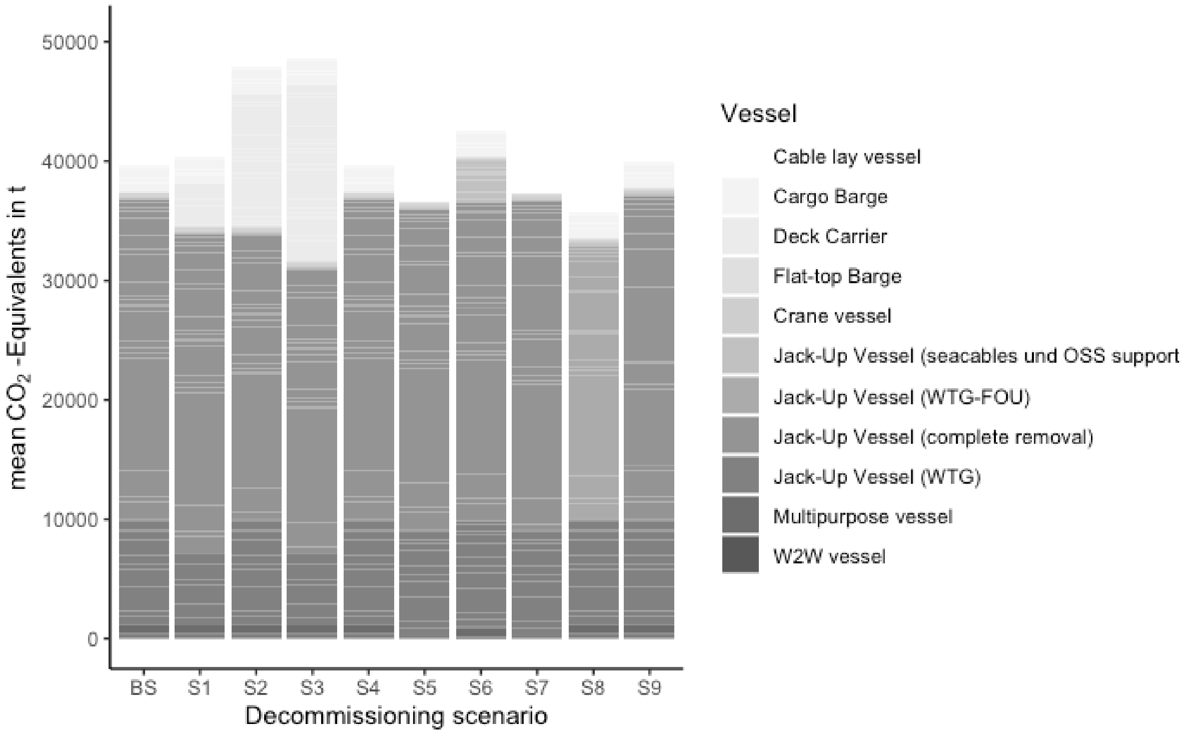

Figure 79: Mean CO_2-equivalents per decommissioning scenario for the different vessels (BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM)

Most studies investigating GHG emissions in context of OWF are life cycle assessments analysing the entire lifetime of an OWF, but focus primarily on construction and the operational phase, while putting less effort in the end-of-life phase (Wang et al. 2019; Wagner et al. 2012; Bonou et al. 2016). (Wagner et al. 2012) however show, that vessels are the main driver for GHG emissions during the operational phase. Hengstler et al. (2021) investigated the GHG emissions of an OWF, that also consists of 80 WTG, but of higher nominal power (8 MW) and, hence, larger installations. For the end-of-life phase they also considered the decommissioning of the export cable to shore and the converter onshore. This might explain their finding of comparable high GHG emissions, 2.0 g CO_2-equivalents/kWh (Hengstler et al. 2021). If the GHG emissions of the *SeeOff* projects were calculated per kWh (operational phase of 25 years with 4 000 full-load hours per year), they would range from 1.41 to 1.84 g CO_2-equivalents/kWh. (Spyroudi 2021) investigated different decommissioning scenarios for an offshore wind farm made up of 35 6 MW wind turbines on MP at water depth of 25 m and a distance from shore of 60 km. For partial decommissioning (removal of turbines and burial of array cables, foundation stay in place) GHG emissions were approx. one third of the GHG emissions of full removal (removal of foundations, turbines and array cables). Our results do not support these finding, as we do not assume that FOU are allowed be left completely in situ. In the research project *SeeOff* partial decommissioning scenarios for FOU are still cut below or above seabed, and the dismantling activities are associated with GHG emissions. Only in *S5 SPL left in situ* and *S7 WTG-FOU: Cut above seabed* GHG emissions are slightly lower as there are no removal activities for the SPL.

Vessel fuel consumptions contribute most to the CO_2-equivalents. In order to reduce these GHG emissions, innovative logistics concepts are required. These might include environmentally-friendly propulsion systems and fuels. Also, novel concepts for dismantling the OWF components offshore should be investigated. A drastic reduction of fuel consumption and, hence, GHG emissions could be achieved if the utilisation of large vessels was forgone or at least reduced.

4.5.3 Resource efficiency

In order to improve material and resource efficiency, prevention of waste, an increase of re-use and recycling are of great relevance. In order to assess resource efficiency of OWF decommissioning, the attribute 'recovery rate' is applied. It is calculated based on the ratio of the recovered amount and the total amount of construction and demolition waste (2011/753/EU). Material recovery 'means any recovery operation, other than energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy. It includes, *inter alia*, preparing for re-use, recycling and backfilling' (2018/851). For the purpose of this analysis, only components and materials brought ashore are considered as waste.

Table 50: Decommissioning scenarios with regards to different scopes of decommissioning of wind turbine generator foundation (WTG-FOU), scour protection layer (SPL) and sea cables

Decommissioning scenarios		WTG-FOU	SPL	Sea cables
BS	Baseline scenario	Cut 1 m below seabed	Removal	Removal
S1	Feeder concept: WTG	Cut 1 m below seabed	Removal	Removal
S2	Feeder concept: WTG-FOU	Cut 1 m below seabed	Removal	Removal
S3	Feeder concept: WTG und WTG-FOU	Cut 1 m below seabed	Removal	Removal
S4	Load-off OSS with SPMT	Cut 1 m below seabed	Removal	Removal
S5	SPL left in situ	Cut 1 m below seabed	Left in situ	Removal
S6	Sea cables left in situ	Cut 1 m below seabed	Removal	Left in situ
S7	WTG-FOU: Cut above seabed	Cut 3 m above seabed	Left in situ	Removal
S8	WTG-FOU: complete removal	Complete removal	Removal	Removal
S9	FOU: Cut with diamond wire saw	Cut 1 m below seabed	Removal	Removal

The recovery rates of the entire OWF are calculated for the different decommissioning scenarios. Six of the decommissioning scenarios (BS, S1-S4 and S9) have no influence on the recovery rate, as amounts and types of material processed do not vary. Four of the decommissioning scenarios (S5, S6, S7 and S8), however, regard different scopes of decommissioning. In these scenarios the amounts or types of materials differ from the baseline scenario (Table 50).

4.5.3.1 Calculation of recovery rate of construction and demolition waste

The recovery rates are calculated in accordance with the recovery rate of construction and demolition waste given by the European Commission in Commission Decision (2011/753/EU):

$$Recovery\ rate\ of\ construction\ and\ demolition\ waste, in\ \% = \frac{Materially\ recovered\ amount\ of\ construction\ and\ demolition\ waste}{Total\ amount\ of\ generated\ construction\ and\ demolition\ waste} \quad \text{[equation 3]}$$

For this purpose, a mass balance of the reference offshore wind farm is compiled. Components and equipment of the OWF are determined regarding their material composition and weights (see Table 26 in chapter 3.1.2). Mass balances are conducted for the different decommissioning scenarios. Subsequently, they are assorted to waste categories and material recovery rates for the waste categories were determined (Table 51). The material recovery rates vary slightly compared to those of Hengstler et al. (2021), though it should be noticed that losses due to collection are not considered in the *SeeOff* project. Most noticeable difference are that Hengstler et al. (2021) do not consider material recovery for rotor blades and energy recovery is assumed for incineration of plastics.

Table 51: Material recovery rate and waste categories for offshore wind farms

Material flow	Material recovery rate	Location of recovery/disposal	Annotations
Stones	100 %	Storage at harbour site	
Rubble		Rubble processing	
F-Gas		F-Gas processing	
SF_6		SF_6 processing	
Lubricants		Lubricants processing	
Diesel		Waste oil processing	
Lead (batteries)		Lead smelter	
Steel	99 %	Steel plant	
Stainless steel		Stainless steel plant	
Cast iron		Iron smelter	
Aluminium		Secondary aluminium smelter	

Material flow	Material recovery rate	Location of recovery/disposal	Annotations
Copper	95 %	Copper smelter	
Glass-fibre reinforced plastic	75 %	Cement plant	25 % energy recovery in in cement kiln
Diverse polymers Domestic waste Bulk waste Miscellaneous	0 %	Incineration	waste incineration plants, if possible with energy recovery

Most of the materials in an OWF have very high material recovery rates of 99 to 100 % as shown for the baseline scenario in Table . Particularly materials with high quantities, e.g., stones and steel have very high material recovery rates.

Table 52: Material flow and mass, material recovery rate and masses recovered of the baseline scenario

Material flow	Mass in t	Material recovery rate in %	Mass recovered in t
Steel	71 921.7	99	71 202.5
Stainless steel	72.8	99	72.1
Cast iron	4 252.2	99	4 209.7
Aluminium	181.8	99	180.0
Copper	2 345.7	95	2 228.4
Class fibre reinforced plastic	4 343.2	75	3 257.4
Stones	116 960.0	100	116 960.0
Rubble (grout)	2 264.0	100	2 264.0
Diverse polymers	386.5	0	0.0
F-Gas	0.5	100	0.5
SF_6	3.4	100	3.4
Domestic waste	16.0	0	0.0
Bulk waste	150.0	0	0.0
Lubricants	116.5	100	116.5
Diesel	17.8	100	17.8
Lead (batteries)	428.4	100	428.4
Miscellaneous	505.9	0	0.0
Total	203 966.5		200 940.7

4.5.3.2 Recovery rates of the decommissioning scenarios

The recovery rates for the decommissioning scenarios are given in Table 54. For the recovery rate no minimal and maximal values are given. Even if variation in the mass balance (Table 26) were considered, the ratio of the materially recovered from demolition waste to the total amount of generated demolition waste would remain the same and, hence, not alter the recovery rate.

In general, recovery rates of the entire OWF for all decommissioning scenarios are high, and always amount up to > 96 %. This is particularly due to the large amounts of steel (41.67 %) and stones (51.67 %) (see Chapter 3.1.2), both having a material recovery rate of 99 %. It's also the amounts of these two materials that alter the recovery rates in the scenarios. Furthermore, it is shown, that difference in scope of decommissioning has an influence on the recovery rate. In S5 the SPL is left in situ. Hence, there are no stones to be recovered and the overall recovery rate is reduced to 96.52 %. The reason for this reduction is that a high proportion of waste with a very high material recovery rate (stones) are not included. The same is true for S7, where the WTG-FOU are cut 3 m above seabed and hence less steel is brought ashore to be recovered. This results in a recovery rate of 96.43 %. In S8 on the other hand, WTG-FOU is removed completely, more steel is recovered and the overall recovery rate of the OWF is slightly increased to 98.56 %. In this scenario, the largest amount of material is returned to the circular economy. Highest recovery rate, however, is yielded for S6, where sea cables are left in situ. This can be attributed to the slightly lower material recovery rate of copper of 95 %. If less copper is recovered, the overall recovery rate increases (Table 53).

In principle, recovery rate is a common attribute to assess resource efficiency. However, when assessing the resource efficiency of different decommissioning scopes of OWF, recovery rates as the only attribute might not be sufficient. The consideration of further attributes, e.g., that take into account the amount and type of materials that remain in the seabed and are not recycled.

Table 53: Recovery rates and masses recovered in t for WTG, WTG-FOU, SPL, sea cables, OSS and the entire OWF for the different decommissioning scenarios

Component	Baseline scenario (and S1-4, S9)		SPL left in situ(S5)		Sea cables left in situ (S6)		WTG-FOU: Cut above seabed (S7)		WTG-FOU: complete removal (S8)	
	Mass flow of waste for recycling in t	recovery rate in %	Mass flow of waste for recycling in t	recovery rate in %	Mass flow of waste for recycling in t	recovery rate in %	Mass flow of waste for recycling in t	recovery rate in %	Mass flow of waste for recycling in t	recovery rate in %
WTG	30 176	94.5	30 176	94.5	30 176	94.5	30 176	94.5	30 176	94.5
WTG-FOU	46 274	99.0	46 274	99.0	46 274	99.0	43 230	99.0	68 450	99.0
SPL	116 960	100.0	0	0.0	116 960	100.0	0	0	116 960	100
Sea cables	3 482	88.4	3 482	88.4	118	88.7	3 482	88.4	3 482	88.4
OSS	4 049	92.5	4 049	92.5	4 049	92.5	4 049	92.5	4 049	92.5
OWF	200 941	98.5	83 981	96.5	197 577	98.7	80 937	96.4	223 117	98.6

Table 54: Recovery rates of the decommissioning scenarios

Decommissioning scenarios		WTG-FOU	Scour protection layer	Sea cables	Recovery rate in %
BS	Baseline scenario	Cut 1 m below seabed	Removal	Removal	98.52
S1	Feeder concept: WTG	Cut 1 m below seabed	Removal	Removal	98.52
S2	Feeder concept: WTG-FOU	Cut 1 m below seabed	Removal	Removal	98.52
S3	Feeder concept: WTG und WTG-FOU	Cut 1 m below seabed	Removal	Removal	98.52
S4	Load-off OSS with SPMT	Cut 1 m below seabed	Removal	Removal	98.52
S5	SPL left in situ	Cut 1 m below seabed	Left in situ	Removal	96.52
S6	Sea cables left in situ	Cut 1 m below seabed	Removal	Left in situ	98.71
S7	WTG-FOU: Cut above seabed	Cut 3 m above seabed	Left in situ	Removal	96.43
S8	WTG-FOU: complete removal	Complete removal	Removal	Removal	98.56
S9	FOU: Cut with diamond wire saw	Cut 1 m below seabed	Removal	Removal	98.52

4.5.4 Biodiversity

Man-made offshore structures attract hard-substrate species, thereby altering the community composition within the area. Increased food availability attracts mobile predators, changing the trophic composition and energy flow and thus altering the local food web (Dannheim et al. 2017; van Hal et al. 2017). Offshore structures can also act as stepping stones, thereby increasing habitat connectivity and benefitting pelagic dispersal and movement of mobile marine species (Dannheim et al. 2017; Hyder et al. 2017). Some species profit from the refugium effect of the offshore structures by using them as feeding, spawning and nursing grounds (Krone et al. 2017; Stenberg et al. 2015; Reubens et al. 2013). OWF decommissioning consequently directly or indirectly impacts the associated benthic communities.

Table 54: Decommissioning scenarios with regard to the scope of decommissioning of WTG-FOU and SPL

	Decommissioning scenarios	WTG-FOU	SPL
BS	Baseline scenario	Cut 1 m below seabed	Removal
S1	Feeder concept: WTG	Cut 1 m below seabed	Removal
S2	Feeder concept: WTG-FOU	Cut 1 m below seabed	Removal
S3	Feeder concept: WTG und WTG-FOU	Cut 1 m below seabed	Removal
S4	Load-off OSS with SPMT	Cut 1 m below seabed	Removal
S5	SPL left in situ	Cut 1 m below seabed	Left in situ
S6	Sea cables left in situ	Cut 1 m below seabed	Removal
S7	WTG-FOU: Cut above seabed	Cut 3 m above seabed	Left in situ
S8	WTG-FOU: complete removal	Complete removal	Removal
S9	FOU: Cut with diamond wire saw	Cut 1 m below seabed	Removal

When OWF are decommissioned, usually the WTG-FOU and SPL are removed, and the hard-substrate habitat is lost. This is also assumed for the baseline scenario and seven alternative decommissioning scenarios (S1-4, S6, S8-9) within the research project *SeeOff*. Two scenarios, however, regard partial decommissioning where hard-substrate is not or not completely removed; scenario *S5 Scour protection left in situ* and *S7 WTG-FOU: Cut above seabed* (Table 55)).

In order to investigate the impact of the decommissioning scenarios on biodiversity, the following question is addressed:

> How much of the species richness can be maintained, if the FOU were to be cut 3 m above seabed instead of being cut 1 m below seabed and if the SPL was left in situ instead of being removed?

The attribute *fraction species richness maintained* is used in order to address this question. This attribute sets the species richness, e.g., at the SPL, in relation to the overall species richness.

4.5.4.1 Data base

In order to assess impacts of decommissioning on the benthic community, data on species associated with hard-substrate over the entire FOU and SPL (if applicable) as well as during and at the end of the operational phase is required. The German licensing authority BSH, however, does not require mandatory environmental monitoring below 10 m water depth and for no longer than a period of 5 years after commissioning. So, no data of German OWF is available to analyse the impact of different scopes of decommissioning on biodiversity. Therefore, a subset of the OWF related data available in the ‘CRITTERBASE (AWI Biodiversity information system)’ of the Alfred-Wegener-Institute (Dannheim et al. (in preparation); Teschke et al. (in review)) is used for the analysis. CRITTERBASE contains data on benthic communities collected in seven OWF, nine oil and gas platforms, two research platforms and one geogenic reef in the south east North Sea.

The data for this analysis is selected on the following criteria

- Project type: Data need to be derived from an OWF. Oil and gas projects were excluded due to the high age of the constructions (build between 1972 and 1999) and the corresponding high community age.
- Sample type: Only Samples collected on the FOU or the SPL are considered.
- Foundation type: jackets, MP and gravity-based FOU are considered.

Therefore, data collected at four offshore projects are selected; the OWF *BelWind*, *C-Powe*r and *Princess Amalia*. The test platform *Fino 1* is treated as OWF, as the foundation is similar to OWF jacket foundations (Table 56).

Table 56: Characteristics of the selected OWF

Project	Country	Year commissioned	Sample type	Foundation type	Number of locations monitored	Max. Sampling depth
BelWind	Belgium	2009	Foundation	Monopiles	2	15 m
			Scour protection layer	---	2	30 m
C-Power	Belgium	2008-2011	Foundation	Gravity-base	2	30 m
			Scour protection layer	---	2	30 m
Fino	Germany	2003	Foundation	Jacket	1	30 m
Princess Amalia	Netherlands	2006-2007	Foundation	Monopiles	4	17 m
			Scour protection layer	---	4	24.5 m

At the four offshore projects with water depth category of >20-25 m data of 36 samples is available, at >25 m data of 32 samples and of 48 samples of SPL (Table 57).

Table 57: Number of samples per sampling depth and for SPL for each foundation and all foundations aggregated

Project	Station	Depth Categories of the WTG-FOU						SPL
		≤ 5 m	>5-10 m	>10-15 m	>15-20 m	>20-25 m	>25 m	
BelWind	BB B8	0	0	23	0	0	0	3
	BB C2	0	0	29	0	0	0	6
C-Power	D5	1	4	66	2	4	0	20
	D6	2	3	16	0	3	0	6
Fino		73	39	10	32	29	32	0
Princess Amalia	T1	11	4	0	4	0	0	3
	T20	12	4	0	4	0	0	3
	T45	12	4	0	4	0	0	4
	T60	12	4	0	4	0	0	3
		123	62	150	50	36	32	48

For data processing and analysis *R: A Language and Environment for Statistical Computing* version 3.6.2 (R Core Team 2019) and *RStudio* version 1.2.1335 (RStudio Team 2018) were used.

4.5.4.2 Calculation of fraction species richness maintained

Baseline scenario and scenarios S1-S4, S6, S8

Scope of dismantling:

- WTG-FOU cut 1 m below seabed or complete removal of MP
- Removal of SPL

If the WTG-FOU were cut 1 m below seabed or completely removed and the SPL would be removed as well, all biodiversity would be removed (0.00 species richness maintained).

Scenario S5 SPL left in situ

Scope of dismantling:

- WTG-FOU cut 1 m below seabed or complete removal of MP
- SPL left in situ

In order to calculate *fraction of species richness maintained* for scenario *S5: Scour protection left in situ*, data of *Fino* is excluded as no samples were collected at SPL. For the other three OWF, the proportion of species richness at SPL is set in relation to the overall species richness of the project.

Species richness and fraction of species richness maintained is calculated for SPL for each WTG-FOU and for all WTG-FOU aggregated. The *fraction of species richness maintained* varies between 0.33 at WTG-

FOU T 22 of OWF *Princess Amalia* (25 species at the SPL (n=3) of 77 overall species (n=23)) and 0.63 at WTG-FOU D5 of the OWF *C-Power* (92 species at the SPL (n=20) of the overall 146 species (n=97)). On average, 0.49 ± 0.10 of the hard-substrate associated species would be maintained if the WTG-FOU were cut 1 m below seabed and the SPL was left in situ (Table 58).

Table 58: Species richness and fraction of species richness and number of samples (n) for all samples and scour protection layer (SPL) only of each foundation and all foundations aggregated

Project	WTG-FOU	All samples			SPL		
		Species richness	Fraction of species richness	n	Species richness	Fraction of species richness maintained	n
BelWind	BB B8	92	1.00	26	39	0.42	3
	BB C2	103	1.00	35	55	0.53	6
C-Power	D5	146	1.00	97	92	0.63	20
	D6	85	1.00	30	50	0.59	6
Princess Amalia	T1	89	1.00	22	42	0.47	3
	T20	77	1.00	23	25	0.33	3
	T45	89	1.00	24	47	0.53	4
	T60	83	1.00	23	36	0.43	3
Mean +/- SD						0.49+ ± 0.10	

Scenario S7 WTG-FOU: Cut above seabed

Scope of dismantling:

- WTG-FOU cut 3 m above seabed
- SPL left in situ

For the analysis of *S7: WTG-FOU cut above seabed*, where also SPL is left in situ, data of all four projects are considered. The mean water depth of the reference OWF is 25 m. If the foundation was cut 3 m above seabed, structures at water depth ≥ 22 m would remain. The SPL would also be left in situ. Therefore, data of samples collected on the WTG-FOU at water depth ≥ 22 m and on the SPL were aggregated and species richness and percentage of species maintained was calculated.

Very high values for fraction of species richness maintained are reached at *Fino* (highest value: 0.81 with 99 species at water depth ≥ 22 m (n=61) of 123 species overall (n=215)). In this project samples were collected even beyond 25 m. For other projects, like *C-Power*, leaving the SPL and part of the WTG-FOU in situ only slightly increases the fraction of species richness maintained (0.66 at D5 and 0.61 at D6) compared to *S5 SPL left in situ* (0.63 at D5 and 0.59 at D6). On average, 0.53 ± 0.14 of the species richness would be maintained if the WTG-FOU were cut 3 m above seabed and the SPL was left in situ (Table 59).

Table 59: Species richness and fraction of species richness and number of samples (n) for all samples and foundation structures (WTG-FOU) ≥ 22 m and scour protection (SPL) aggregates of each foundation and all foundations aggregated

Project	WTG-FOU	All samples			WTG-FOU ≥ 22 m and SPL		
		Species richness	Fraction of species richness	n	Species richness	Fraction of species richness maintained	n
BelWind	BB B8	92	1.00	26	39	0.42	3
	BB C2	103	1.00	35	55	0.53	6
Fino		123	1.00	215	99	0.81	61
C-Power	D5	146	1.00	97	96	0.66	22
	D6	85	1.00	30	52	0.61	9
Princess Amalia	T1	89	1.00	22	42	0.47	3
	T20	77	1.00	23	25	0.33	3
	T45	89	1.00	24	47	0.53	4
	T60	83	1.00	23	36	0.43	3
Mean +/- SD						0.53 ± 0.14	

4.5.4.3 Assessment of decommissioning scenarios

An overview on the *fraction of species richness maintained* per decommissioning scenario is given in Table . In order to test whether the decommissioning scenarios influence the *fraction of species richness maintained*, the non-parametric Kruskal-Wallis test is performed (R Core Team 2019). It shows that there is a significant difference in the decommissioning scenarios (chi-squared = 17.871, df = 2, p-value < 0.05). Subsequently, a post hoc test (Dunn's test) is conducted to reveal which decommissioning scenarios are different. The *fraction of species richness maintained* for the two partial decommissioning scenarios (Scenario 5 and 7) is significantly different from the (complete) removal (BS, S1-S4, S6 and S8-S9) (p-values < 0.05), but not from each other (p-value = 0.75) (Figure 80). Also, there are differences at the different types of FOU; the *fraction of species richness maintained* is lower at MP than at gravity-base foundations. The difference between *S5 SPL left in situ* and *S7 WTG-FOU: Cut above seabed* can be deduced for the jacket foundation, whose *fraction of species richness maintained* is higher than the other foundation types.

Table 60: Fraction of species richness maintained for the decommissioning scenarios

Decommissioning scenarios		WTG-FOU	SPL	Fraction of species richness maintained
BS	Baseline scenario	Cut 1 m below seabed	Removal	0.00
S1	Feeder concept: WTG	Cut 1 m below seabed	Removal	0.00
S2	Feeder concept: WTG-FOU	Cut 1 m below seabed	Removal	0.00
S3	Feeder concept: WTG und WTG-FOU	Cut 1 m below seabed	Removal	0.00
S4	Load-off OSS with SPMT	Cut 1 m below seabed	Removal	0.00
S5	SPL left in situ	Cut 1 m below seabed	Left in situ	0.49 ± 0.10
S6	Sea cables left in situ	Cut 1 m below seabed	Removal	0.00
S7	WTG-FOU: Cut above seabed	Cut 3 m above seabed	Left in situ	0.53 ± 0.14
S8	WTG-FOU: complete removal	Complete removal	Removal	0.00
S9	FOU: Cut with diamond wire saw	Cut 1 m below seabed	Removal	0.00

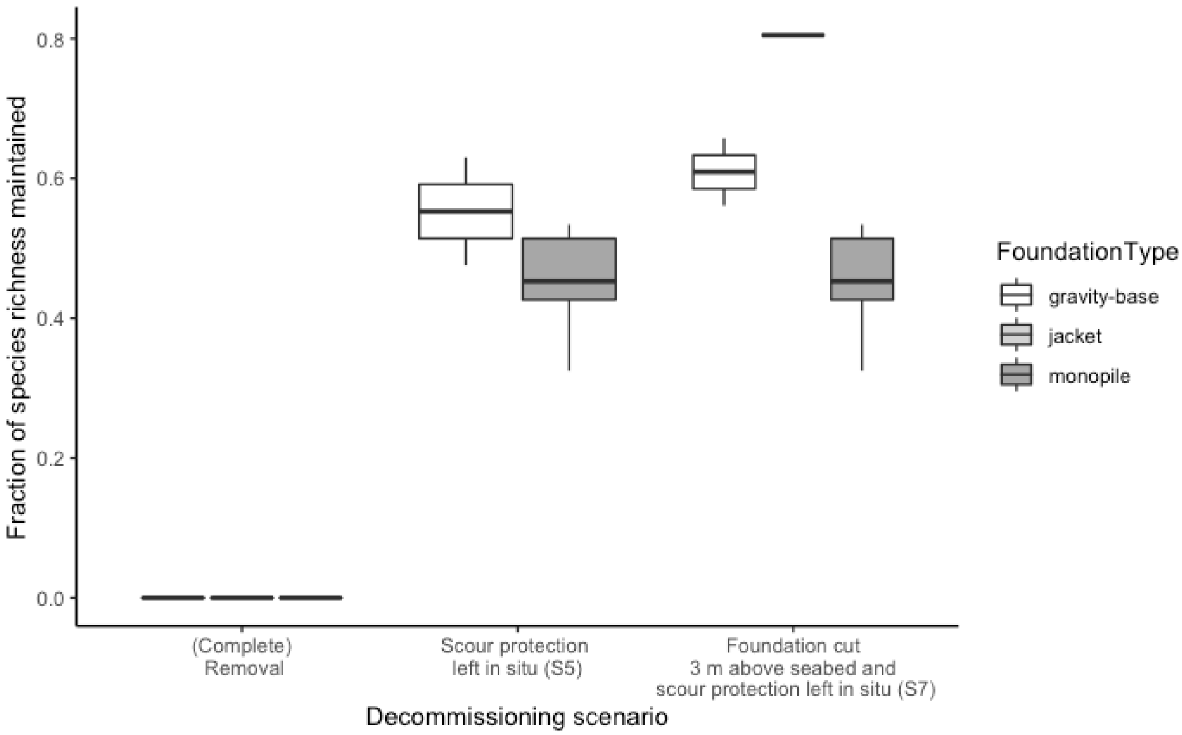

Figure 80: Fraction of species richness maintained for the decommissioning scenarios: (complete) removal of foundation structure and scour protection layer, scour protection layer left in situ and foundation structure cut 3m above seabed, and scour protection layer left in situ.

Our analysis suffers from two principal shortcomings: 1. OWF differ in their habitats and their associated communities, and 2. systematic and long-term surveys and in-depth knowledge on cause-effect relationships are missing. In particular, there is no monitoring data over the entire WTG-FOU or the SPL nor is data over the entire operational period of German OWF available. the OWF-related biological data available from CRITTERBASE of the Alfred-Wegener-Institute is the best data available to assess impact of different decommissioning scope on the benthic community.

Some argue, that if the WTG-FOU and SPL were removed, the status before the construction of OWF would be restored. Our analysis, however, clearly shows that the more hard-substrate remains, the more biodiversity is maintained. Leaving the SPL in situ contributes most to maintaining species richness. If the WTG-FOU were cut 3 m above seabed (S7) *fraction of species richness maintained* would be slightly higher (0.53 ± 0.14) than if the WTG-FOU were cut 1 m below seabed (S5) (0.49 ± 0.10), the difference, however, is not significant (0.75). However, only few investigations on the WTG-FOU close to the seabed or on the SPL are available. In the data set of our analysis, samples at the FOU beyond a water depth of 20 m were collected in only two projects (FINO and C-Power) and three stations, respectively (Table). The low sample size affects the value of the test results accordingly. Studies, however, show that a diverse community develops around such structures (Mesel et al. 2015; Krone et al. 2017; Coolen et al. 2020b; Degraer et al. 2019). Coolen et al. (2020a) investigated biodiversity and biomass macrofauna for decommissioning decisions of Dutch oil and gas installations and found that the macrofaunal community would benefit from partial decommissioning. But with the current data basis of OWF the actual cause-effect relationships remain uncertain and data-based recommendations for decommissioning are a challenge (Degraer et al. 2019; Dannheim et al. 2020). In order to support decommissioning decisions on German OWF, more research on the bottom part of WTG-FOU and the SPL is needed.

For sufficient amount of data, not only MP, but also jackets and gravity-based foundations were considered in this analysis. Even though these foundations are structurally very different, Coolen et al. (2020b) found that substrate types have a much greater impact on species composition than on species richness. However, a greater data availability including research on different foundation types would enable a more differentiated analysis.

Though not an artificial reef according to Jackson and Miller (2009, p. 4) (an artificial reef 'is a submerged structure placed on the seabed deliberately, to mimic some characteristics of a natural reef.'), OWF are well known for their artificial reef effect. The structures are colonised by hard-substrate species altering the trophic composition of the associated soft-bottom and epifauna communities (Dannheim et al. 2017). These communities, their composition, the biodiversity and the abundance of species, however, change over the years (Dannheim et al. 2020; Mesel et al. 2015; Degraer et al. 2019). So, investigations shortly after the construction of OWF or after only a couple of operational years most likely do not reflect the possible situation at the end of the operational phase. In order to make a well-founded statement about the benthic community and possible effects of decommissioning, further monitoring during the operational phase is required.

Even though being human-introduced structures, the artificial reef effects of OWF and the associated enhanced biodiversity can be considered as ecological beneficial (Methratta and Dardick 2019; Reubens et al. 2013). The increased abundance and diversity within the OWF lead to an increased availability of food for benthivorous and piscivorous species. By maintaining some of the hard-substrate OWF structures not only the benthic but also the associated fish community could benefit. The changes in hard-substrate communities, however, also affect the surrounding soft-sediment community, though actual cause-effect-relationships are not fully understood yet (Degraer et al. 2019; Dannheim et al. 2020; Hutchison et al. 2020, p. 58-69). Effects on the associated fish and soft-sediment communities should hence also be the subject of further investigations.

The lack on in-depth knowledge of the long-term effect of the OWF installations on the benthic and fish community hampers our assessment of OWF decommissioning scenarios. Statements on whether it is more beneficial to leave the SPL or part of the WTG-FOU in situ or to remove all structures to restore the initial state are preliminary and also depend on the community in perspective. Our analysis, however, shows that leaving the SPL in situ clearly enhances the richness of species associated with hard-substrate. Cutting the WTG-FOU above the seabed seems to increase species richness, too, but to a lesser extent. However, systematic studies are required in order to allow reliable statements about the actual impacts of partial decommissioning on the biodiversity. This includes surveys during the operation phase and at the end of the operational lifetime of the OWF over the entire WTG-FOU and the SPL.

4.5.6 Overview of results of decision criteria

The results of the calculated decision criteria per decommissioning scenario in chapter 4.5.1 to 4.5.5 are summarized in Table 64. For detailed elaboration on the assumptions and the procedure for the calculation as well as interpretation of results, see the corresponding chapter.

The results show the varying performance of the decision criteria per decommissioning scenario and that it is not possible to select the most sustainable decommissioning scenario on this basis. This highlights the dilemma of the multi-objective problem, which can be solved using the multi-criteria decision analysis (chapter 4.6).

Table 64: Mean values and ± SD or minimal (Min) and maximal (Max) values of the decision criteria per decommissioning scenario (BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM).

		Decision criteria												
		€ / MW			t CO_2-Equivalents			Recovery rate in %	Fraction of species richness maintained			Hazard measure		
		- SD	Mean	+ SD	Min	Mean	Max		- SD	Mean	+ SD	Min	Mean	Max
Decommissioning scenario	BS	268 987	329 756	390 524	33 775	43 860	54 485	98.52	0.00	0.00	0.00	914.95	930.99	948.99
	S1	312 637	381 240	449 842	33 762	44 599	57 816	98.52	0.00	0.00	0.00	947.32	951.46	960.07
	S2	396 649	488 310	579 971	38 728	52 164	67 618	98.52	0.00	0.00	0.00	943.58	959.01	974.30
	S3	439 707	543 393	647 080	38 715	52 903	70 949	98.52	0.00	0.00	0.00	975.33	976.77	988.70
	S4	268 690	329 395	390 100	33 765	43 847	54 470	98.52	0.00	0.00	0.00	914.95	930.99	948.99
	S5	215 793	272 233	328 674	30 833	40 556	50 817	96.52	0.39	0.49	0.59	914.95	930.99	948.99
	S6	275 780	332 331	388 882	34 564	44 661	55 297	98.71	0.00	0.00	0.00	611.18	631.42	656.54
	S7	188 158	241 505	294 851	31 378	41 194	51 945	96.43	0.41	0.58	0.75	911.02	926.65	941.37
	S8	287 478	373 054	458 629	29 571	40 712	52 100	98.56	0.00	0.00	0.00	956.07	964.64	964.99
	S9	411 793	474 794	537 794	38 032	44 235	50 451	98.52	0.00	0.00	0.00	772.27	788.56	811.13

4.6 Multi criteria decision analysis

Multi-criteria decision analysis (MCDA) is a tool that supports decision making incorporating multiple objectives. In the following we describe the method for the assessment of sustainability selected in the research project SeeOff.

There is a great diversity of MCDA methods, e.g., (Wątróbski et al. 2019) list 56 multi-criteria methods and their combinations. There are different approaches on how to structure MCDA methods. One is to structure them in Multi-Objective Decision Making and Multi-Attribute Decision Making. In Multi-Objective Decision Making it is assumed that there is a continuous set of alternatives and it aims to find the optimal solution for the decision problem. In Multi-Attribute Decision Making on the other hand, there is a discrete number of alternatives of which the best alternative for the decision problem is to be found. Multi-Attribute Decision Making methods can be subdivided into 'European school', where it is assumed that decision makers are not clearly aware of their own preference, and 'American school', where it is believed that the decision makers know about their preference. (Geldermann and Lerche 2014)

The weighted sum model belongs to the latter school and is applied in order to assess sustainability of the decommissioning scenarios. In the weighted sum model the following steps are followed (according to Bundesministerium des Inneren/Bundesverwaltungsamt 2018):

1. Determination and weighting of decision criteria
2. Assessment of decommissioning scenarios
3. Calculation and interpretation of decision scores

4.6.1 Determination and weighting of decision criteria

The decision criteria for economic, environmental and social aspects were determined and elaborated in chapter 4.1. Priority analysis was carried out in order to assess the criteria weights. The method is based on the pairwise comparison of two criteria and awarding of points according to Table 65. (Bundesministerium des Inneren/Bundesverwaltungsamt 2018)

Table 65: Awarding of points for the priority analysis for criteria weighting (according to Bundesministerium des Inneren/Bundesverwaltungsamt 2018)

	Criterion A	Criterion B
Criterion A is as important as criterion B	1	1
Criterion A is more important than criterion B	2	0
Criterion B is more important than criterion A	0	2

For the assessment of the criteria weights, a survey with the stakeholder associated with or interested in OWF decommissioning was carried out. The survey ran for one week with the tool Aulis (powered by ILIAS v6.12 2021-10-20). The survey participants are first asked to assign themselves to predefined stakeholder groups (see Table 4 in chapter 1.3). Subsequently they rated the criteria regarding their importance by pairwise comparison according to Table 65. As multiple stakeholders weight the criteria, mean values of the points are calculated and summed up per criterion.

76 surveys are answered completely and, hence, qualify for further analysis. One third of the survey participants assign themselves to the stakeholder main group *Research institute / university*, most of which with an expertise in environment or offshore wind energy. Other stakeholders frequently participating in the survey are offshore wind farm *operators* (16 %), *planning and service companies* (12 %), *consulting companies,* mostly engineering offices, (11 %) and *ministry / authorities* (11 %) (Table 66).

Table 66: Survey participation per Stakeholder main group

Stakeholder main group	Survey participation	
	Number	Percentage
Research institute / university	25	33 %
Operator	12	16 %
Planning and service companies	9	12 %
Consulting company	8	11 %
Ministry/authority	8	11 %
Logistic company	4	5 %
other	3	4 %
Dismantling / Repowering company	2	3 %
Associations / representatives	2	3 %
Waste management	1	1 %
Certification / Inspection body	1	1 %
Supplier	1	1 %
	76	100 %

Criteria weights are calculated and analysed in two ways (Figure 85).

1. The weights are averaged for all stakeholders.
2. The analyses are conducted separately for each of the five main stakeholders mentioned above.

For all stakeholders (weight: 3.86) and the individual stakeholder groups *safety at work* is the most important criterion. *Economic efficiency* is the least important criterion for all stakeholders (weight: 1.86). For *planning / service* and c*onsulting companies* the criterion *GHG emission* is less important than the other criteria.

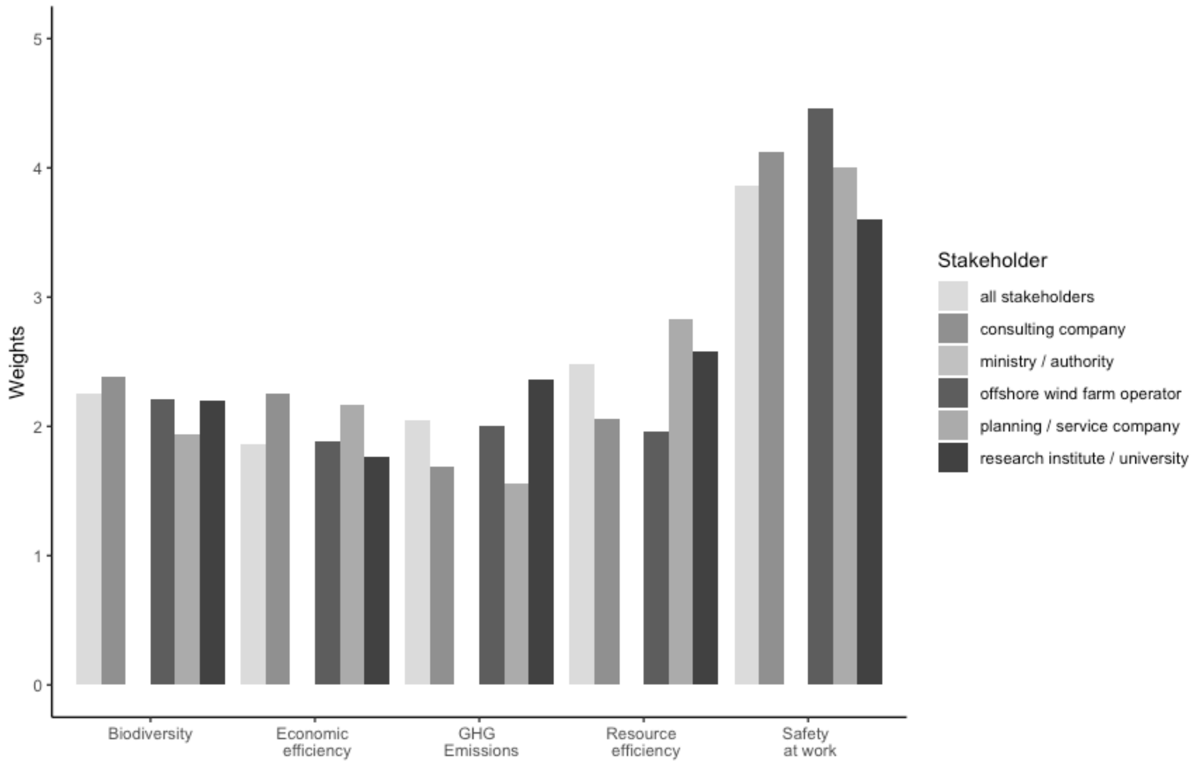

Figure 85: Weights for Biodiversity, Economic efficiency, GHG emissions, Resource efficiency and Safety at work by all stakeholders, consulting company, ministry / authority, offshore wind farm operator, planning / service company and research institute / university.

For the other criteria the tendency of preference is less clear and varies among the stakeholders. For all stakeholders, *resource efficiency* (weights: 2.48) is the second most important criterion, *biodiversity* (weight: 2.25) the third, and *GHG emissions* (2.05) the fourth.

4.6.2 Assessment of decommissioning scenarios

The decommissioning scenarios are examined to determine the extent to which they meet the objectives of sustainable OWF decommissioning. For this purpose, points on a scale of 0 to 10 are assigned to the decommissioning scenarios for the fulfilment each criterion (CF = points for criteria fulfilment); with 0 points (=criterion not fulfilled) being assigned to the worst performance, 10 points (= excellent criteria fulfilment) to the best performance, and the other points are distributed proportionally. Table 67 shows the assignment of points for fulfilment of the decision criteria (according to Bundesministerium des Inneren/Bundesverwaltungsamt 2018).

Table 68 shows the points awarded for the fulfilment of the sustainability criteria for each decommissioning scenario.

Table 67: Awarding of point for fulfilment of the decision criteria

Points	Criteria fulfilment	Decision criteria									
		Mean € / MW		Mean t CO_2-Equivalents		Recovery rate in %		Fraction species richness maintained		Mean hazard measure	
0	not fulfilled	>	543 393	>	52 903	<	96.43		0.00	>	976.77
1	just sufficient	543 392	509 849	52 902	51 530	96.42	96.67	0.01	0.05	975.77	937.39
2	sufficient	509 848	476 306	51 529	50 158	96.66	96.93	0.06	0.12	936.39	899.02
3	sufficient - satisfactory	476 305	442 763	50 157	48 786	96.92	97.18	0.13	0.18	898.02	860.65
4	satisfactory	442 762	409 220	48 785	47 414	97.17	97.43	0.19	0.25	859.65	822.28
5	satisfactory - good	409 219	375 676	47 413	46 043	97.42	97.69	0.26	0.31	821.28	783.91
6	good	375 675	342 133	46 042	44 671	97.68	97.94	0.32	0.38	782.91	745.53
7	good - very good	342 132	308 590	44 670	43 299	97.93	98.19	0.39	0.44	744.53	707.16
8	very good	308 589	275 047	43 298	41 927	98.18	98.45	0.45	0.51	706.16	668.79
9	very good - excellent	275 046	241 504	41 926	40 555	98.44	98.70	0.52	0.57	667.79	630.42
10	excellent	<	241 505	<	40 556	>	98.71	>	0.58	<	631.42

Table 68: Point for fulfilment (CF_{ij}) of the sustainability criteria for each decommissioning scenario (BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM)

		Decision criteria				
		(Present value of) costs / decommissioned MW	CO_2-Equivalents	Recovery rate	Fraction of species richness maintained	Hazard measure
Decommissioning scenario	BS	7	7	9	0	2
	S1	5	7	9	0	1
	S2	2	1	9	0	1
	S3	0	0	9	0	0
	S4	7	7	9	0	2
	S5	8	10	9	8	2
	S6	7	7	10	0	10
	S7	10	9	0	10	2
	S8	6	9	9	0	1
	S9	3	7	9	0	5

4.6.3 Calculation and interpretation of decision scores

For calculating decision scores, a decision matrix is constructed consisting of *n* decommissioning scenarios (DS_1, ..., DS_n) and *m* decision criteria (SC_1, ..., SC_m). The points for the criteria fulfilment CF_{ij} (i = 1, ..., n and j = 1, ..., m) are multiplied with the criteria weights (CW_j) and summed up per scenario (Table) (according to Bundesministerium des Inneren/Bundesverwaltungsamt 2018). The following equation shows the calculation oft he decision score DS_i for each scenario i.

$$DS_i = \sum_{j=1}^{m} CF_{ij} * CW_j \qquad \text{[equation 6]}$$

Based on the decision scores, ranks of 1 to n are assigned to the scenarios with 1 being the scenario with the highest decision score and, hence, being preferred by the decision makers.

Table 69: Decision matrix

	SC_1 CW_1	SC_2 CW_2	... ...	SC_m CW_m	Decision scores
DS_1	CW_1*CF_{11}	CW_2*CF_{12}	...	CW_m*CF_{1m}	$\sum_{j=1}^{m} CF_{1j} * CW_j$
DS_2	CW_1*CF_{21}	CW_2*CF_{22}	...	CW_m*CF_{2m}	$\sum_{j=1}^{m} CF_{2j} * CW_j$
...	...	...	...	...	...
DS_n	CW_1*CFn_1	CW_2*CF_{n2}	...	CW_m*CF_{nm}	$\sum_{j=1}^{m} CF_{ij} * CW_j$

Decision scores of the different decommissioning scenarios

For the decommissioning scenarios, the decision matrix (Table 70), the decision scores (Figure 86) and the performance of the different decommissioning scenario per decision criteria (Figure 88 to 96) are presented below. From the perspective of all stakeholders, scenario *S6 sea cables left in situ* has the highest decision score (90.8) and is thus the most favourable alternative of those available for sustainable offshore wind farm decommissioning in our analysis. It is the scenario with the best performance in the two most relevant decision criteria; at safety at work, i.e., the lowest level of hazards, and resource efficiency; i.e., having the highest recovery rate. Scenario *S5 SPL left in situ* is the scenario with the second highest decision value (83.4). This scenario has the lowest GHG emissions of all scenarios and yields high points for the other decision criteria as well.

Table 70: Decision matrix, weighted criteria values and ranks (1 = scenario with the highest decision score to 9 = scenario with the lowest decision score) for the decommissioning scenarios (BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM)

		(Present value of) costs / decommissioned MW	CO_2-Equivalents	Recovery rate	Fraction of species richness maintained	Hazard measure	Decision scores	Ranks
		1.86	2.05	2.48	2.25	3.86		
Decommissioning scenario	BS	13.02	14.35	22.32	0.00	7.72	57.4	6
	S1	9.30	14.35	22.32	0.00	3.86	49.8	7
	S2	3.72	2.05	22.32	0.00	3.86	32.0	8
	S3	0.00	0.00	22.32	0.00	0.00	22.3	9
	S4	13.02	14.35	22.32	0.00	7.72	57.4	6
	S5	14.88	20.50	22.32	18.00	7.72	83.4	2
	S6	13.02	14.35	24.80	0.00	38.60	90.8	1
	S7	18.60	18.45	0.00	22.50	7.72	67.3	3
	S8	11.16	18.45	22.32	0.00	3.86	55.8	5
	S9	5.58	14.35	22.32	0.00	19.30	61.6	4

Scenario *S3 Feeder concept: WTG and WTG-FOU* has the lowest decision values (22.3) and is thus the least favourable option for sustainable offshore wind farm decommissioning in our analysis. It yielded the lowest points for economic efficiency, GHG emissions, biodiversity and safety at work. *S2 Feeder concept: WTG-FOU* is the scenario with the second lowest decision scores (32.0). The feeder concept for the WTG-FOU requires more large vessels, i.e., one JUV and two deck carriers, while the overall dismantling period (45 weeks) is not noticeably shorter than for the baseline scenario (46 weeks) (see chapter 4.4.1.). Consequently, approximately the same operation duration with more large vessels results in higher costs and GHG emissions. The high level of hazards is mostly due to the loading and sea fastening activities.

All other scenarios yield decision scores between 49.8 (*S1 Feeder concept: WTG)* and 61.6 (*S9 FOU: cut with DWCM*). The baseline scenario lies with a decision score of 57.4 in the middle.

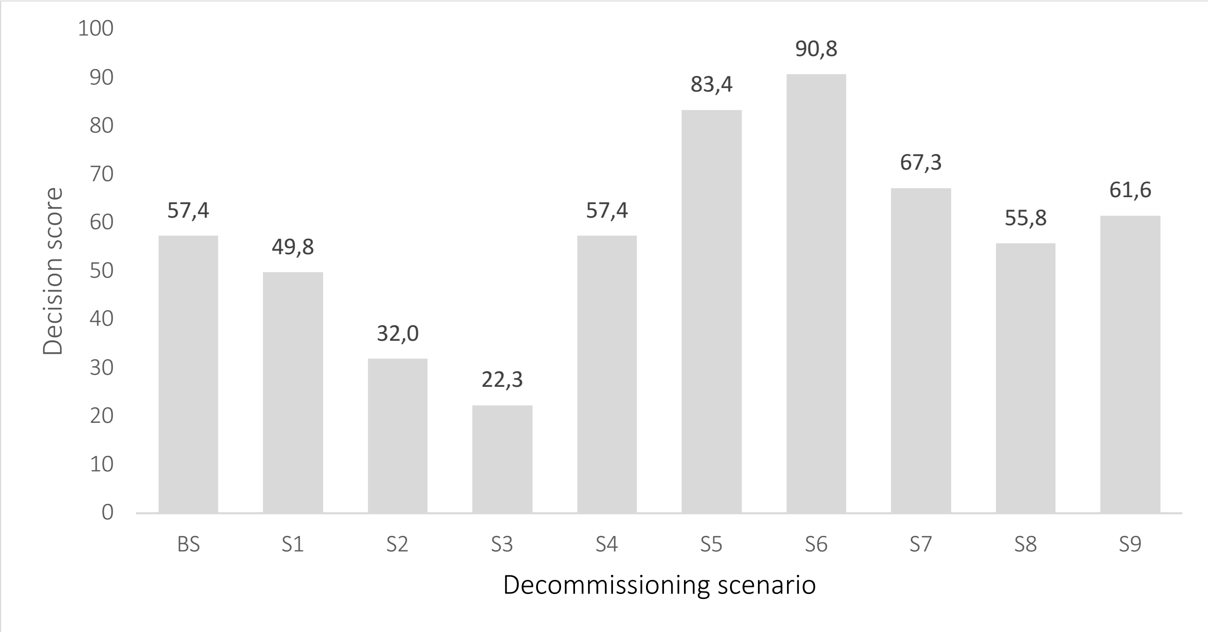

Figure 86: Decision score for the decommissioning scenarios (BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM)

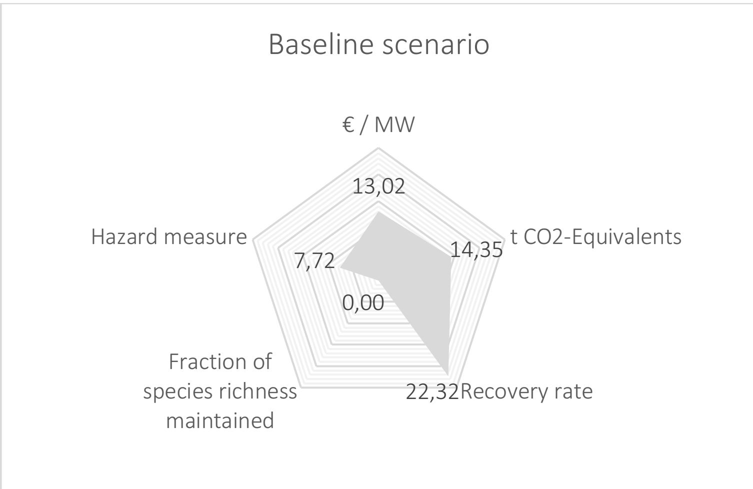

Figure 87: Performance of the baseline scenario per decision criterion

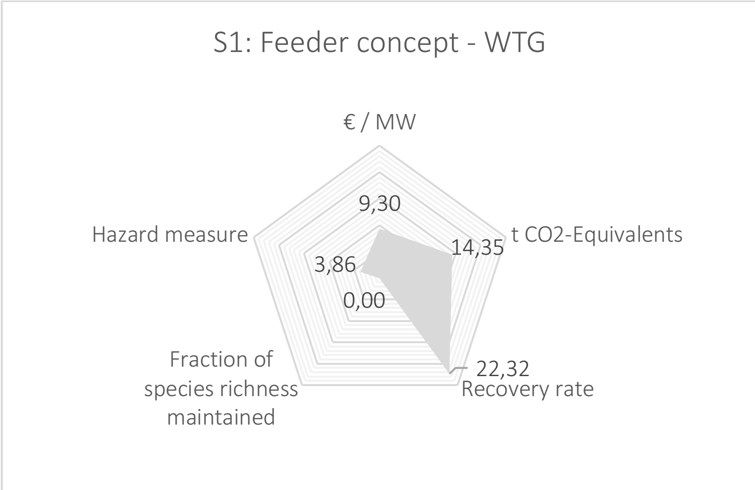

Figure 88: Performance of decommissioning scenario *S3: Feeder concept – WTG* per decision criterion

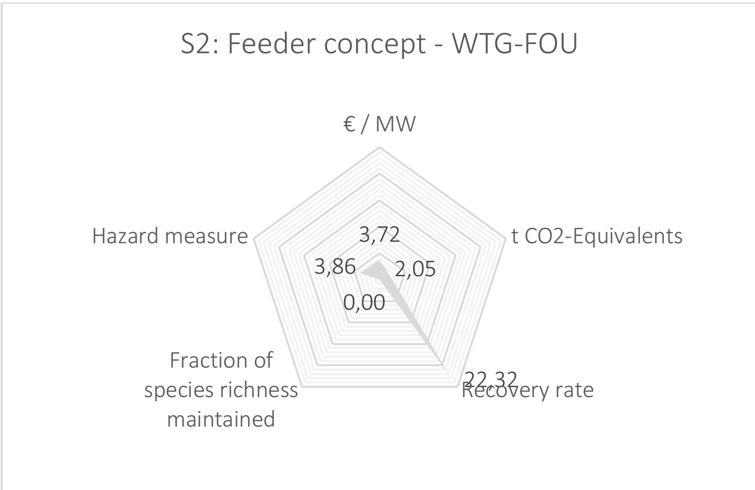

Figure 89: Performance of decommissioning scenario *S3: Feeder concept –WTG-FOU* per decision criterion

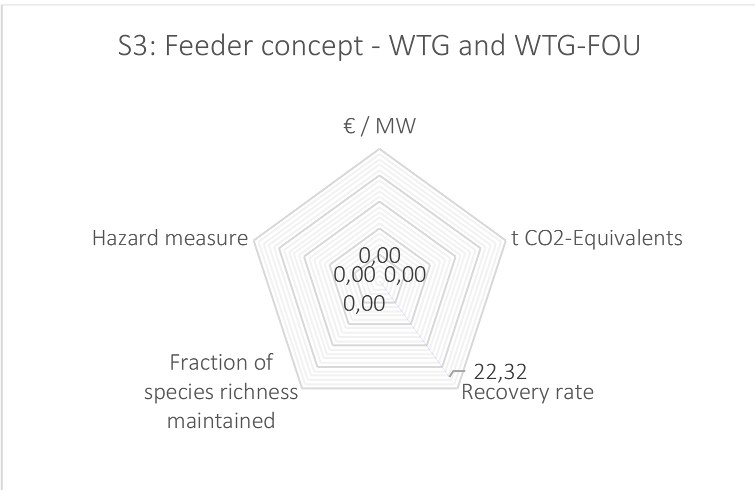

Figure 90: Performance of decommissioning scenario *S3: Feeder concept – WTG and WTG-FOU* per decision criterion

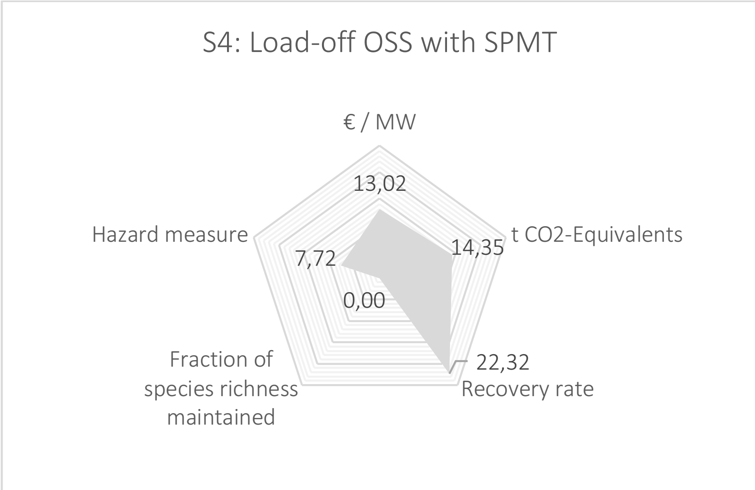

Figure 91: Performance of decommissioning scenario *S4: Load-off OSS with SPMT* per decision criterion

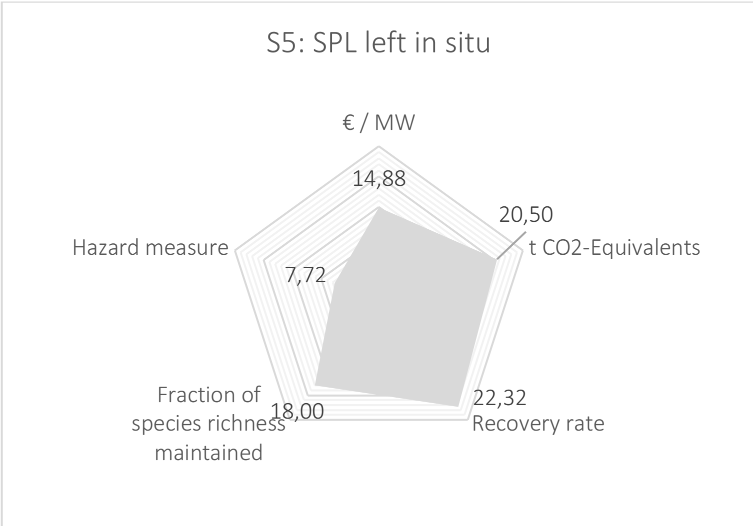

Figure 92: Performance of decommissioning scenario *S5: SPL left in situ* per decision criterion

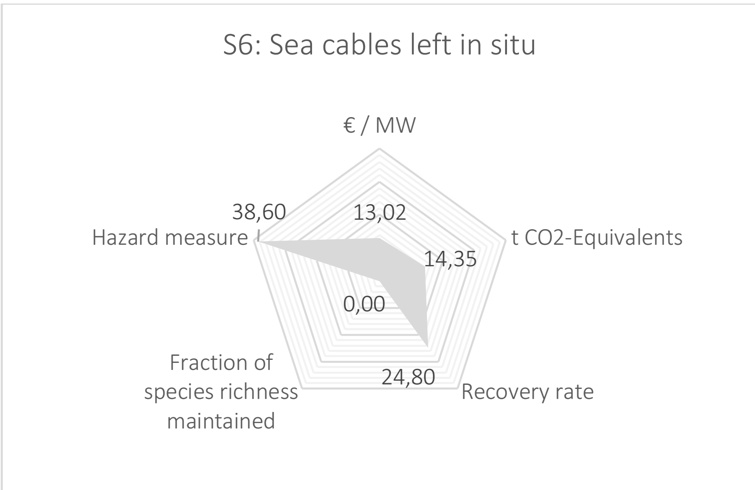

Figure 93: Performance of decommissioning scenario *S6: Sea cables left in situ* per decision criterion

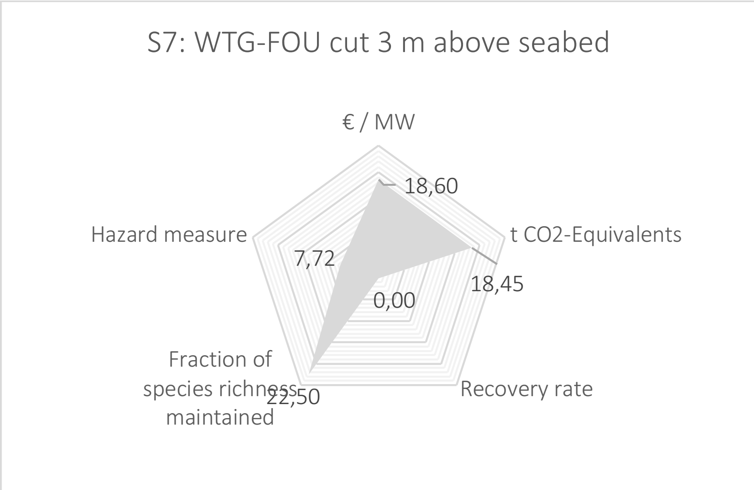

Figure 94: Performance of decommissioning scenario *S7: WTG-FOU cut 3 m above seabed* per decision criterion

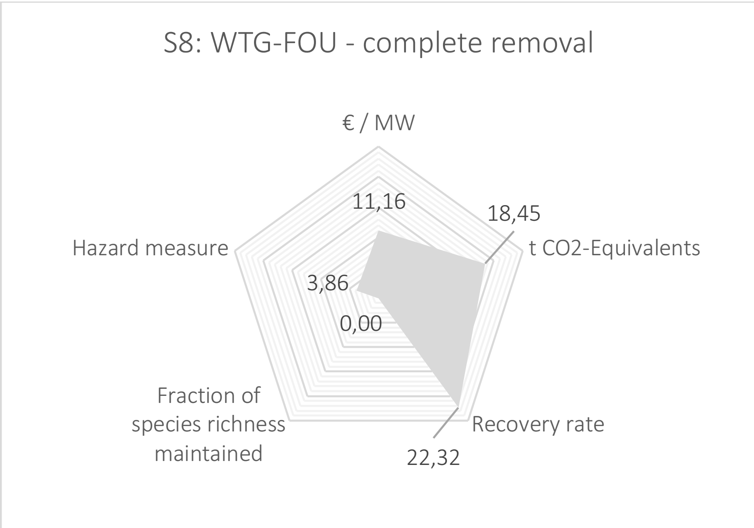

Figure 95: Performance of decommissioning scenario *S8: WTG-FOU: complete removal* per decision criterion

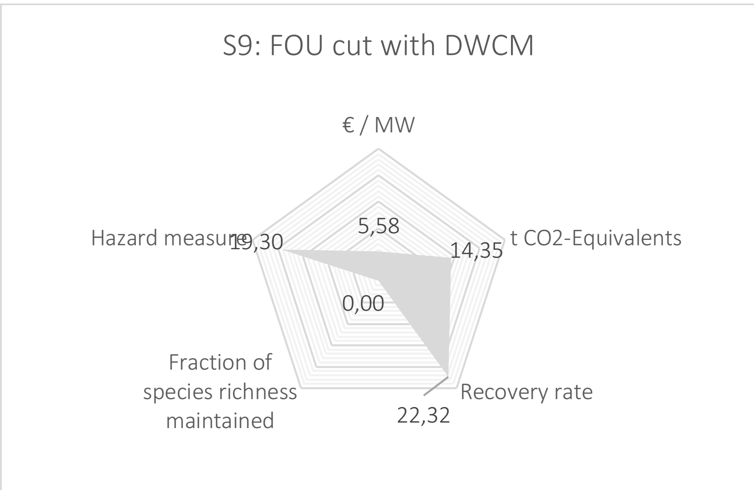

Figure 96: Performance of decommissioning scenario *S9: FOU cut with DWCM* per decision criterion

Sensitivity analysis

In order to determine how strongly the criteria weighting influences the outcome, a sensitivity analysis was conducted.

Analysis with criteria weights of different stakeholders

It is to be checked whether the determined criteria weights of different stakeholders have an influence on the results of the weighted sum analysis. For this purpose, the results of the priority analysis for different stakeholder groups (*research institute/university, operator, planning/service company, consulting company and authority/ministry*) are used (Figure 85 in chapter 4.6.1). These criteria weights are now used to calculate the overall utility values. Figure A 1 shows that decision scores vary, but the overall ranking of the decommissioning scenarios is not changed by the criteria weights of the different stakeholders. *S6 Sea cables left in situ* continues to be the scenario with the highest score and *S3 Feeder concept: WTG and WTG-FOU* the one with the lowest score.

Analysis with regard to different perspectives of sustainability

The second sensitivity analysis addresses the question as to whether very strong positions for one criterion (focus) above the other influences the decision scores and consequently the ranking of the decommissioning scenarios. Therefore, the criteria weights were set so that one criterion was given a very high value (0.8) and the others were given a very low value (0.05) (Table 71).

Table 71: Criteria weights for the sensitivity analysis

Focus	Decision criteria				
	(Present value of) costs / decommissioned MW	CO_2-Equivalents	Recovery rate	Fraction of species richness maintained	Hazard measure
Focus Economy	0.8	0.05	0.05	0.05	0.05
Focus GHG	0.05	0.8	0.05	0.05	0.05
Focus Resource efficiency	0.05	0.05	0.8	0.05	0.05
Focus Biodiversity	0.05	0.05	0.05	0.8	0.05
Focus Safety at work	0.05	0.05	0.05	0.05	0.8

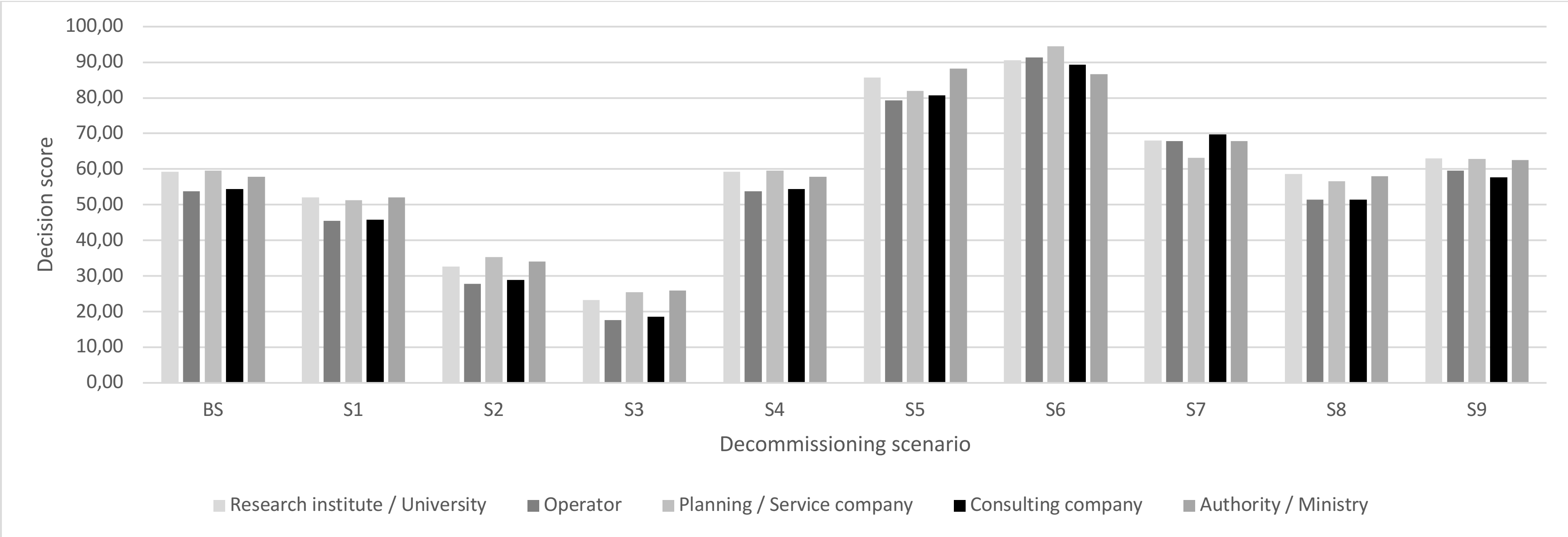

Figure 97: Decision scores for the different decommissioning scenarios per stakeholder (BS=baseline scenario, S1= Feeder concept: WTG, S2= Feeder concept: WTG-FOU, S3= Feeder concept: WTG and WTG-FOU, S4=Load-off OSS with SPMT, S5=SPL left in situ, S6=Sea cables left in situ, S7=WTG-FOU: Cut above seabed, S8=WTG-FOU: complete removal, S9=FOU: Cut with DWCM))

Table 72 shows that the scenarios *S5 SPL left in situ* and *S6 sea cables left in situ* are the scenarios in which four out of the five decision criteria reach very high decision scores. For GHG emission the highest decision values were reached in *S5 SPL left in situ*, for resource efficiency and safety at work in *S6 sea cables left in situ* and for economic efficiency and biodiversity in *S7 WTG-FOU: cut above seabed*. Our results suggest, that scenarios with partial decommissioning yield the highest decision scores.

Table 72: Ranks (1 = scenario with the highest decision score to 9 = scenario with the lowest decision score) for the decommissioning scenarios per focus

	Decommissioning scenarios	Focus Economy	Focus GHG	Focus Focus Resource efficiency	Focus Biodiversit y	Focus Safety at work
BS	Baseline scenario	4	5	4	5	6
S1	Feeder concept: WTG	5	6	5	6	7
S2	Feeder concept: WTG-FOU	7	7	6	7	8
S3	Feeder concept: WTG und WTG-FOU	8	8	7	8	9
S4	Load-off OSS with SPMT	4	5	4	5	6
S5	SPL left in situ	2	1	2	2	3
S6	Sea cables left in situ	3	4	1	3	1
S7	WTG-FOU: Cut above seabed	1	2	8	1	4
S8	WTG-FOU: complete removal	5	3	3	4	5
S9	FOU: Cut with diamond wire saw	6	5	4	5	2

The least favourable decommissioning scenario, from a sustainability point of view, is *S3 Feeder concept: WTG and WTG-FOU*. In this scenario the lowest decision scores for each criterion weighting are yielded. The low performance of this decommissioning scenario is closely followed by *S2 Feeder concept WTG-FOU*. So, the feeder concept for the WTG-FOU does not appear to be a sustainable decommissioning scenario. The feeder concept for the WTG, however, has a much better performance from the economic efficiency and GHG emission perspective.

The sensitivity analysis reveals that relevance imposed on the decision criteria does not substantially change the finding; *S6 sea cables left in situ* and *S5 SPL left in situ* are always the most favourable options while *S3 Feeder concept: WTG and WTG-FOU* and *S2 Feeder concept: WTG-FOU* are the least favourable scenarios.

5 Discussion

5.1 Critical review

5.1.1 Review of applied methods and quality of research results

For the determination of sustainable decommissioning strategies for OWF a process-based procedure is developed (see chapter 4.2). To approach the largely unknown field of OWF decommissioning by investigating and assessing decommissioning processes has proved to be very successful and purposeful. The processes are documented in writing and models. Data on relevant information to calculate decision criteria (e.g., costs, durations or vessel fuel consumptions) are collected in a large data frame. Thereby, a comprehensive knowledge and data base is built and ambiguities are continuously revealed and resolved.

The decommissioning scenarios compared in this study also demonstrate to be suitable in type and number. The scenarios are diverse by considering different decommissioning technologies and vessel concepts as well as different scopes of decommissioning.

The calculation of the decision criteria can only be as good as the information and data provided allows. As outlined in chapter 4.2 the collection of this information and data was very challenging, but resulted in a large knowledge and data base. Even more detailed investigations and particularly more experiences in OWF decommissioning will surely extend and improve this collection.

The Monte Carlo simulation, as conducted here, is a reasonable method to compare the expected costs of decommissioning scenarios. However, there are several limitations concerning our cost simulations. First, the results, i.e., net expected costs, suggest some degree of certainty because of their presentation in absolute numbers. Nevertheless, the reader should keep in mind that the net expected costs are still estimates based on assumptions instead of exact cost calculations. Second, the results do not show the complete costs, since we left out all costs that occur identically in all scenarios, e.g., crew transfer vessels and traffic safety vessels. Third, the resources considered for our cost simulation reflect the state-of-the-art decommissioning techniques and have been chosen mostly based on the installation experiences of our interviewees. However, there are resources, i.e., vessels and tools, that are subject to technical development. The cost rates of such resources under development are unknown to date and are not part of our cost simulations. Fourth, there are significant uncertainties regarding the use durations of the resources. Both, the range of the durations and their cost could decrease over time as more experience is gained with decommissioning of OWF. Fifth, we conducted the simulations based on current cost rates. Specifically, with respect to the future development of vessel cost rates, our interviewees expressed varying expectations: some expect that many of the needed vessels will be relocated to South East Asia for installation purposes and, consequently, vessel cost rates will increase significantly. Other interviewees expect that the vessels formerly used for installations will become useless for future installations because of the increasing size of WTGs. Consequently, the latter interviewees expect a glut of vessels and decreasing prices. In addition, there could be significant salary increases depending on political developments or price changes regarding materials which are subject to resale, e.g., aluminium and copper. Such price changes would have significant impact on the results.

The greatest influence on the GHG emissions can be attributed to the vessel fuel consumptions (see chapter 4.5.2). Information on fuel consumption for all vessels investigated, however, is basically impossible to obtain, as vessel fuel consumptions are confidential. In the research project *SeeOff*, fuel consumptions are estimated based on the vessel propulsion power. This is a common procedure that allows for a standardized calculation of fuel consumptions. Input of actual vessel fuel consumptions might alter GHG emissions accordingly.

The recovery rate is a common tool to assess resource efficiency. It considers only those components or material flows that are generated as waste in the harbour and are recycled. The findings of the research project *SeeOff* show that all decommissioning scenarios have high recovery rates. However, when comparing decommissioning scenarios with different scopes of decommissioning, this attribute might lead to false conclusions. For instance, the recovery rate is higher, if sea cables were left in situ (S6) than if they were removed. At first sight, this might seem counter intuitive, though this can be attributed to the fact, sea cables consist of materials with low material recovery rates. Here, other attributes might be more meaningful, e.g., that set the amounts of materials that are removed and, hence, are materially recovered, in relation to the overall amount of material that could be recovered.

The scarce data base regarding monitoring data at the bottom of the FOU and the SPL is a great challenge to assessing impacts on the local marine biodiversity. The findings of the research project *SeeOff* unsurprisingly show that leaving the SPL in situ has a great impact on the species richness that would be maintained. But in order to make more statements regarding the influence of OWF decommissioning on the local marine environment, further research is needed.

Hazard assessments are required by law prior to any work as well as risk analysis within the scope of executing the planning of decommissioning (BSH 2021). The derivation of a hazard measure indicator as proposed to compare different decommissioning scenarios can be helpful in the initial assessment and in the identification of processes and scenarios with higher hazard potential. The parameter of the activity duration shows a major contribution to the results. Furthermore, it could serve in the early stages of the project phases of an OWF to consider and construct technical safety barriers or implement technical measures to effectively reduce hazards later in the decommissioning phase. However, to apply the method for every process within the *SeeOff* project is too extensive and therefore was not feasible for all processes within the system boundary.

MCDA is generally a suitable tool to support decision making processes considering multiple objectives. In the research project *SeeOff*, criteria are weighted by priority analysis and a weighted sum model is applied to analyse the decommissioning scenarios (see chapter 4.6). Pairwise comparison appears to be a suitable tool to weight the decision criteria. To judge whether one criterion is as or more important than another criterion is easily understandable and simple to accomplish and, hence, very suitable for a survey. The scale on which the criteria are judged, however, could be more differentiated. Using a different scale e.g., to give 1 point if the criteria were of equal importance and up to 9 points if one criterion was extremely more important than the other (as in the analytic hierarchy process (Montis et al. 2005, pp. 99-133), would result in more differentiated weights.

Within the research project, two surveys were conducted on the importance of the decision criteria. Firstly, stakeholders who are directly or indirectly involved in OWF decommissioning were questioned (priority analysis and Figure 84 in chapter 4.6). Secondly, an acceptance survey was conducted with the general public (Figure 21 in chapter 1.4). The results show that the groups attach different relevance to the criteria. The general public attaches by far the greatest importance to the most environmentally friendly technologies. Among the stakeholders involved in dismantling, the aspect of occupational safety is rated most important. This can be explained by the fact that safety aspects are all the more important the closer the actual connection to decommissioning is. It is also possible that the general public cannot assess the importance of occupational safety in dismantling due to a lack of knowledge.

The weighted sum model is a widely known MCDA and easy to apply. In the research project *SeeOff* it is decided that 0 points are assigned to the scenarios with the worst performance, 10 points to the scenario with the best performance and the other points are distributed proportionally (see chapter 4.6). This procedure is straight-forward and can be applied on all decision criteria consistently. For some of the decision criteria, this results in a distribution of points with misleading interpretation. For the recovery rate, for instance, a single scenario receives 0 points and all other scenarios 9 or 10 points (see Table 68). This implies that the performance of the one scenario is much worse than the other. In fact, all of the scenarios have a very high recovery rate in general and in the scenario with the "worst" performance the FOU are cut above seabed, resulting in less steel being fed to the waste management and consequently a lower recovery rate. It should, however, be kept in mind that when cutting above seabed 33 metres of MP remain in the seabed, but when cutting below seabed 29 metres of MP still remain in the seabed. Other methods to define the performance of the decommissioning scenario, e.g., instead of assigning points in the manner presented above, a decision maker rating the decommissioning scenario with focus on the fulfilment of the decision criteria, might lead to different results.

5.1.2 Review of partial decommissioning scenarios

The results of the MCDA show that under consideration of the five decision criteria the partial decommissioning scenarios are more favourable than other scenarios. Our evaluations show, that partial decommissioning performs well regarding economic efficiency, greenhouse emissions, local marine biodiversity and occupational health and safety. If partial decommissioning of OWF is to be considered, other aspects should be taken in to account as well.

For example, subsequent use of the OWF area is an important issue. This topic, however, was not part of our investigations. Due to the high expansion targes (Chapter1), it can be assumed that the areas will be used for new energy generation after decommissioning.

If another OWF was to be installed in the same area, leaving sea cables in situ would most likely result in problems for the installation of new IAC. Remaining SPL, however, should not impede the installation of new WTG or IAC. Whether new WTG could be installed at the exact same location as the decommissioned structures, even if they were completely removed, e.g., by vibratory extraction, requires further investigations. A new OWF layout would probably differ from the old one anyway due to increased turbine size.

To what extent or in which manner leaving sea cables, SPL or parts of the FOU in situ would impair the safety and efficiency of traffic, requires further investigations.

The results of our analysis imply that leaving SPL and/or parts of the FOU in situ, rather contributes to maintaining local biodiversity of the benthic community associated with hard-substrate than endangers the marine environment. For a holistic analysis of impacts on the marine environment, further investigation at the bottom of the FOU and the SPL, as well as of the soft-sediment and fish community are required.

Also, it should be considered, if and to what extent partial decommissioning contradicts SDG 14 ‘Conserve and sustainably use the oceans, seas and marine resources for sustainable development’ (UN 2020). Marine pollution should be avoided and reduced, but also adverse impact on marine ecosystems should be prevented. Thus, by removing SPL, for instance, the benefits of avoiding potential pollution or at least waste, should be weighed against the impact on the marine environment by large-scale dredging of the seabed.

On the other hand, it must be considered that materials remaining in/on the seabed (e.g., steel structures) cannot be fed into the circular economy as secondary raw materials. Closed material loops contribute to increasing the value of our resources as well as reducing GHG emissions.

5.2 Transferability on other offshore wind farms and offshore wind farm components

5.2.1 Transferability of dismantling techniques, logistics and decommissioning processes

The transferability or applicability of the information presented in this handbook concerning the dismantling procedures, logistics and the course of the dismantling processes essentially depends on three factors: the location of the wind farm in a geographical and geological context, the system components used and the type of grid connection to the wind farm, compared to the reference OWF. The reference system investigated within *SeeOff* is representative of many OWF commissioned up to 2015 and hence for the first OWF to be decommissioned in the German Exclusive Economic Zone (EEZ). However, especially for the first years of offshore wind energy use, there were different approaches for the FOU types, connection systems or turbine technologies. This applies to wind turbines as well as to offshore substations and converters.

Due to the variability of OWF in geographical position and technology, no generally valid statements can be made about the decommissioning of offshore windfarms. This applies to dismantling procedures, the vessels to be used or the process of dismantling. Dismantling and logistics concepts depend highly on the location of the OWF, including hydrological aspects like water depth and seabed morphology, as well as the distance from and types of harbours. It is likely that not only a single harbour, but different harbours specialized on certain OWF components will be involved in decommissioning. Also, the reuse of OWF components is an option that is likely to be considered in other projects.

Some of the procedures described in this manual, such as WAS or diamond wire sawing, (see chapter 3.3.1) can be applied on different FOU types. However, similar to vessel logistics, these also face a technical development as wind turbines and their foundations are increasing in their dimensions and subject to constant development.

Dismantling processes and logistics of the reference OSS can be transferred to converter platforms, e.g., *SylWin alpha*, only to a limited extent. The installations are structurally similar in their basic features; both consist of a topside with several decks and a jacket FOU. However, they differ considerably in their dimensions (reference OSS: 42 x 36 x 30 m, *SylWin alpha*: 83 x 56 x 50 m) and weight (reference OSS: topside 3 000 t and jacket 1 100 t, *SylWin alpha*: topside 15 000 t and jacket 10 000 t). For the de-installation of the reference OSS, it is assumed that the jacket is cut below the topside by oxy-fuel flame cutting and the driven piles are cut by WAS. It can be assumed on a case-by-case basis that the diameters and wall thicknesses of the converter are within the application range of the cutting techniques selected for the reference OSS. However, for Abrasive Water Jetting from the inside, access to the piles and grout connections needs to be clarified. If cutting from the inside is not possible, cutting from the outside can be considered. The topside and jacket of the reference OSS are lifted by a crane vessel and placed on a barge, i.e., similar logistics to the installation phase will be required. However, due to the dimensions of the converter topside and jacket structure and the environmental conditions (e.g., water depth), the development of a specific dismantling and logistics concept is necessary, as there are only very few vessels worldwide with the required crane capacity. The converter was also installed using a ballasting procedure for the jacket structure and a subsequent float-over procedure for the topside. The development of alternative, innovative dismantling procedures and logistics concepts also seems necessary for the de-installation of the converter.

Special engineering is therefore always required for dismantling planning and especially for dismantling offshore. Possible material fatigue and corrosion of individual components and connections due to the loads during the operating phase must also be taken into account. So far, apart from the dismantling of the wind turbine (in the best case), no components can be dismantled non-destructively. Individual approaches exist for OSS that have self-erecting platforms, such as Baltic 2 (Alstom 28.10.2015) or systems for lowering the topside (Arup o.J.).

In contrast to the dismantling processes offshore, dismantling processes ashore are rather transferable to other OWF or system components such as the converter. An internal analysis of the comminution and recycling processes for the converter has revealed many intersections. However, the conditions at the harbour site have to account for the dimensions and processing of the material quantities, e.g., space requirements, surface loads, required onshore logistics, a sufficiently good hinterland connection a.s.o. Another challenge beside the increasing diameter and weight of the system components of OWF, is the changing material composition. For example, neither carbon fibre composites nor permanent magnets are installed in the components of the wind turbines in the reference OWF. For wind turbines of larger power classes and rotor diameters, on the other hand, carbon fibre composites are used to reduce the weight and increase the stability of rotor blades. With new materials, disposal and recycling processes must be developed and, if necessary, dismantling processes adapted. This also applies to the processing of permanent magnets for the recovery of critical metals (including neodymium, dysprosium).

The dismantling and disassembly procedures ashore are largely transferable, with the exception of the above-mentioned material changes for more powerful WTG, since OWF consist mainly of steel and SPL material in terms of weight. The optimisation potential here lies in the cutting speed during flame cutting for steel (see chapter 3.5.2). Depending on the system component (WTG, OSS, cable or even converter), the demand and size of onshore resources (e.g., cranes) and construction machinery will differ. For assemblies that are to be prepared for reuse, a piece-large or non-destructive pre-assembly or coring is required. Other factors influencing the conditions under which onshore dismantling and disassembly can be carried out are (licensing) legal requirements and conditions relating to immission, environmental and health protection.

5.2.2 Transferability of assessment approach

The approach to identify sustainable decommissioning strategies presented in Chapter 4 can be transferred to other OWF and other OWF components. The system boundaries can be extended, e.g., to also include the converter and the export cable for grid connection.

The objectives for sustainable OWF decommissioning should be defined for each project anew. As most OWF are unique, objectives are unique as well. At least one criterion per economic, environmental and social category should be defined. Within the research project *SeeOff*, the environmental category was presented with three aspects; for other projects, the focus might be laid upon GHG emissions only. Within the social category, offshore rescue (times) (Jürgens and Weinrich 2015), work organisation (Mette et al. 2019) or unmanned operations could be of relevance as well. For the economic category, other objectives, however, are not expedient. The central economic objective is to reduce decommissioning costs and all others, e.g., risk minimization, would only be intermediate objectives for minimizing costs here.

Depending on the project-specific criteria and decommissioning scenarios, the decision criteria are calculated. The method of calculation and interpreting decision criteria defined in the research project *SeeOff* can be transferred to other OWF and OWF components. Regarding the results, it can be expected that the major GHG emissions derive from the vessels, irrespective of the OWF. However, the logistical concept for the decommissioning might have a great influence on the GHG emissions and this can be expected to be unique for each OWF. Impacts of the local marine biodiversity will also vary between OWF. However, as outlined in chapter 0, the data availability required for assessing species richness at the bottom of the FOU and the SPL is scarce, so that for the majority of OWF this criterion is challenging to assess. The hazard measure used as an indicator for the occupational safety of processes is also transferable to other OWF. However, it requires in-depth knowledge of the work processes and the associated hazards at a high level of detail that might differ between OWF. The cost simulation method is extendable to further components, e.g., the converter and the export cable for grid connection, and transferrable to other OWF. In order to do so, the input data have to be adjusted. Especially the resources with the durations of their use and the related cost rates might differ. Furthermore, the risks for each OWF must be assessed individually, especially due to weather and technical uncertainties. Additionally, the tax situation needs to be assessed for every OWF. There might be differences according to the location, e.g., if the OWF is located within the twelve-mile-zone instead of the EEZ.

MCDA can be applied on any OWF project. The methods selected to assess sustainable OWF decommissioning strategies depends on the person(s) applying the method and the decision maker. The methods applied in the research project *SeeOff*, however, are comparably simple to understand and easy to apply, so they can be suggested to be used for other OWF decommissioning projects as well.

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Erratum to Publication VIII

Assessment of sustainable strategies for offshore wind farm decommissioning and Discussion

Excerpts of Chapter 4 and 5 in Handbook of offshore wind farm decommissioning: Framework, technologies, logistics, processes, scenarios and sustainability

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When revising the MCDA results, three mistakes in the publication were detected; (i) wrong values for the point of the pairwise comparison were entered in table 65 (ii) the weights of the decision criteria *resource efficiency* and *biodiversity* were interchanged for the calculations and (iii) the wrong number of points for the criteria fulfilment of *resource efficiency* were assigned to alternative A_6.

(i) In table 65 of chapter 4.6.1 wrong values for the points of the pairwise comparison were put down. Correct is, that 0 points were awarded for one criterion being less important than the other, 0.5 point for being equally important and 1 point for being more important.

As the correct values were used in the calculation of the criteria weights, this mistake has no influence on the subsequent results.

(ii) In chapter 4.6 (and the subsequent calculations) the weights of the decision criteria *resource efficiency* and *biodiversity* were interchanged. The correct weight for the criterion *resource efficiency* is 2.25 and for *biodiversity* 2.48.

(iii) In chapter 4.6.2 the wrong number of points (9 points) were assigned to decommissioning alternative *S5 (A_6) SPL left in situ*. With a recovery rate of 96.52%, alternative *S5 (A_6) SPL left in situ* should have received 1 point (see Table 67).

Mistakes (ii) and (iii) resulted in minor deviations of the decision scores and raking of the decommissioning scenarios (Table 70-Erratum), i.e., the ranks of following decommissioning alternatives were interchanged:

- decommissioning alternatives *S5 (A_6) SPL left in situ* (false rank: 2, correct rank: 3) and *S7 (A_8) WTG-FOU: Cut above seabed* (false rank: 3, correct rank: 2)
- decommissioning alternatives *BS (A_1) baseline scenario* (false rank: 6, correct rank: 5), *S4 (A_5) Load-off OSS with SPMT* (false rank: 6, correct rank: 5) and *S8 (A_9) WTG-FOU: complete removal* (false rank: 5, correct rank: 6)

The deviations in the decision scores and ranking are only minor and do not alter the overall interpretation of the results.

Table 70-Erratum: Decision matrix, weighted criteria values and ranks (1 = scenario with the highest decision score to 9 = scenario with the lowest decision score) for the decommissioning scenarios (BS (A_1)=baseline scenario, S1 (A_2)= Feeder concept: WTG, S2 (A_3)= Feeder concept: WTG-FOU, S3 (A_4)= Feeder concept: WTG and WTG-FOU, S4 (A_5)=Load-off OSS with SPMT, S5 (A_6)=SPL left in situ, S6 (A_7)=Sea cables left in situ, S7 (A_8)=WTG-FOU: Cut above seabed, S8 (A_9)=WTG-FOU: complete removal, S9 (A_{10})=FOU: Cut with DWCM)

		(Present value of) costs / decommissioned MW	CO_2-Equivalents	Recovery rate	Fraction of species richness maintained	Hazard measure	Decision scores	Ranks
		1.86	2.05	2.25	2.48	3.86		
Decommissioning scenario	BS (A_1)	13.03	14.32	20.25	0.00	7.72	55.33	5
	S1 (A_2)	9.31	14.32	20.25	0.00	3.86	47.74	7
	S2 (A_3)	3.72	2.05	20.25	0.00	3.86	29.88	8
	S3 (A_4)	0.00	0.00	20.25	0.00	0.00	20.25	9
	S4 (A_5)	13.03	14.32	20.25	0.00	7.72	55.33	5
	S5 (A_6)	14.89	20.46	2.25	22.32	7.72	67.65	3
	S6 (A_7)	13.03	14.32	22.5	0.00	38.62	88.47	1
	S7 (A_8)	18.62	18.41	0.00	24.80	7.72	69.56	2
	S8 (A_9)	11.17	18.41	20.25	0.00	3.86	53.70	6
	S9 (A_{10})	5.59	14.32	20.25	0.00	19.31	59.47	4

IX Multi-criteria decision analysis for sustainable offshore wind farm decommissioning

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X Impact of decision criteria weighting on the ranking of offshore wind farm decommissioning alternatives

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CHAPTER 4

SYNTHESIS

4 Synthesis

Decision makers for offshore wind farm (OWF) decommissioning are challenged by the lack of experiences and best-practices. They require, therefore, a different basis for their decision-making. This thesis aims to support decision makers to make qualified and comprehensible decisions for sustainable OWF decommissioning. It addresses the assessment of the sustainability of selected decommissioning alternatives taking associated uncertainty into consideration.

In this chapter, first, multi-criteria decision analysis (MCDA) as a tool to assess the sustainability of OWF decommissioning is discussed with focus on the applicability, advantages and limitations of the different methods applied in this study (chapter 4.1.1). Thereafter, the five decision criteria for the assessment of the sustainability considered in this study, i.e., *greenhouse gas (GHG) emissions*, *resource efficiency*, *biodiversity*, *costs* and *hazards,* are elaborated on (chapter 4.1.2). The investigated alternatives of OWF decommissioning are discussed in chapter 4.1.3.

Chapter 4.2 addresses further considerations, beginning with other decommissioning alternatives (chapter 4.2.1) and the subsequent use of the decommissioned area (chapter 4.2.2). Other decision criteria for the assessment of the sustainability are suggested in chapter 4.2.3. Thoughts on the improvement of the data and knowledge base are presented in chapter 4.2.4. Chapter 4.2.5 concludes with recommendation for further research.

4.1 Assessment of the sustainability of alternatives of offshore wind farm decommissioning

4.1.1 Multi-criteria decision analysis methods

Each MCDA starts with familiarization with the decision problem, in this case the decommissioning project. The top-down approach as suggested in publication IV is advisable in order to get an overview of the high-level decommissioning processes and, thereafter, steadily gaining detailed insight into the operational processes. When facing OWF decommissioning different alternatives can be considered regarding e.g., dismantling technologies, vessel fleet or partial decommissioning. Limiting factors, such as site conditions, technological limitations or regulatory requirements, reduce the number of possible alternatives. In this study, ten alternatives were investigated. With considering a finite number of uniquely differentiable alternatives and aiming to identify the best solution amongst the available options, multi-attribute decision analysis methods are suitable (opposing to multi-objective decision analysis that have a process-oriented design and focus on finding the optimal solution amongst an infinite number of alternatives) (Geldermann & Lerche, 2014; Malczewski & Rinner, 2015). In publication VIII the MCDA method weighted sum model (WSM) was applied. It is an easily comprehensible and applicable method and, therefore, also suitable for the partially non-scientific audience of the research project *SeeOff*. In publication IX the uncertainty associated with the OWF decommissioning was appreciated by applying fuzzy MCDA methods: fuzzy SAW, fuzzy TOPSIS and fuzzy VIKOR. Both investigations, publications VIII and IX, show, that MCDA is suitable to identify sustainable OWF decommissioning alternatives. The different MCDA methods resulted in similar, yet different, ranking of the alternatives (Figure 2). With all methods, decommissioning alternatives considering feeder concepts (A_2 *Feeder concept: WTG*, A_3 *Feeder concept: WTG-FOU* and A_4 *Feeder concept: WTG and WTG-FOU*) are mostly ranked lowest and partial decommissioning alternatives (A_6 *SPL left in situ,* A_7 *Sea cables left in situ* and A_8 *WTG- FOU: Cut above seabed*) are mostly ranked highest. A_9 *WTG-FOU: Complete removal* and A_{10} *FOU: Cut with diamond wire saw* are the scenarios, that have the widest range of ranks occupied.

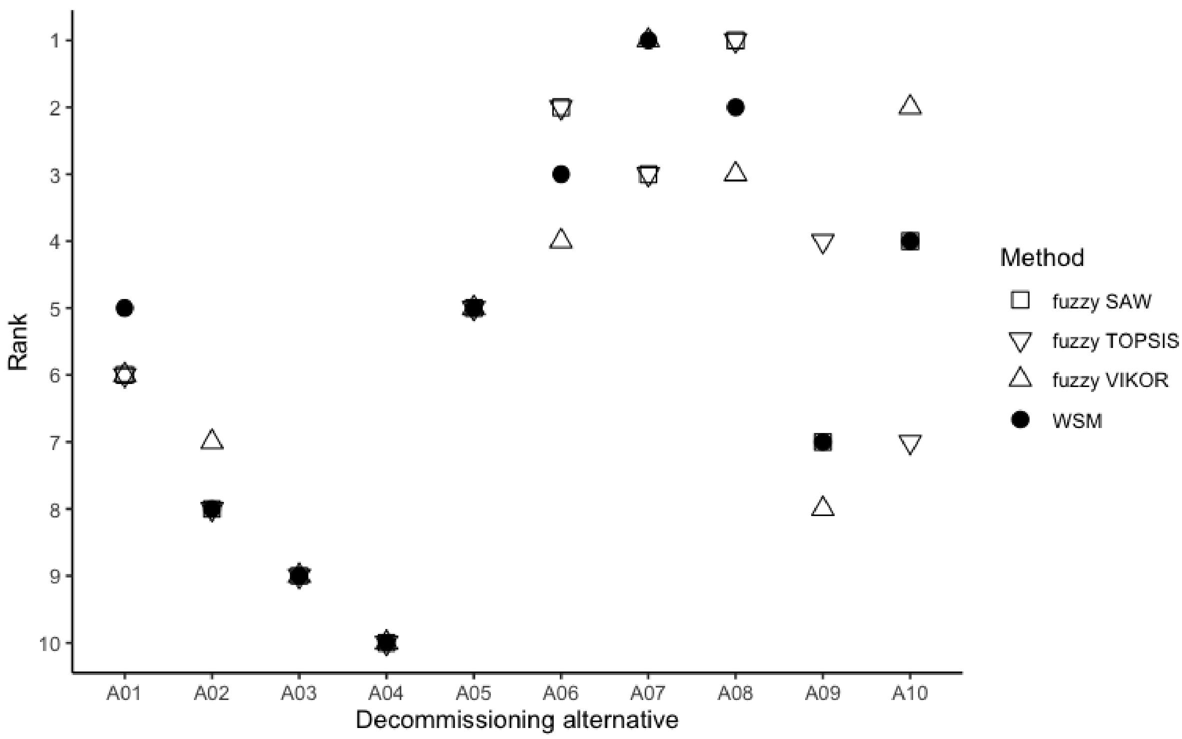

Figure 2: Ranks per decommissioning alternative of the difference MCDA methods with weighted decision criteria stakeholder (A_1 = Baseline scenario, A_2 = Feeder concept: WTG, A_3 = Feeder concept: WTG-FOU, A_4 = Feeder concept: WTG and WTG-FOU, A_5 = Load-off offshore substation with SPMT, A_6 = SPL left in situ, A_7 = Sea cables left in situ, A_8 = WTG- FOU: Cut above seabed, A_9 = WTG-FOU: Complete removal and A_{10} = FOU: Cut with diamond wire saw)

Differences in MCDA results can be attributed to the normalization approach and aggregation function for ranking of the alternatives (Opricovic & Tzeng, 2004). In this study, the normalization is not likely to affect the outcome of the fuzzy MCDAs, as normalization in all three fuzzy methods led to similar intermediate results (publication IX). In fuzzy TOPSIS and fuzzy SAW linear scale transformation was applied for normalization, in fuzzy VIKOR linear normalization was used (publication IX). In the WSM with assigning points for the criteria fulfilment, a very different approach was applied, which also takes the best and worst performances into consideration (publication VIII). The results suggest that the difference in the rankings is due to the aggregation approaches in each MCDA method. In the WSM, the weighted criteria fulfilment is summed up (publication VIII). In Fuzzy SAW the total fuzzy scores are defuzzified and summed up (publication IX). In fuzzy TOPSIS relative closeness to the ideal solution (CC_i) is calculated based on the distances of each alternative to the fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS). Here the distances are summed without accounting for the relative importance of the criteria (Opricovic & Tzeng, 2004). Akin to the fuzzy TOPSIS, in fuzzy VIKOR the distance of an alternative to the ideal solution is considered. The VIKOR index is calculated based on the two 'boundary measures' S_j and R_j and is an 'aggregation of all criteria, the relative importance of the criteria, and a balance between total and individual satisfaction' (Opricovic & Tzeng, 2004). 'The effects of the different aggregation approaches become obvious, when comparing decommissioning alternatives *A_9 WTG-FOU: Complete removal* (rank 4 with fuzzy TOPSIS, rank 8 with fuzzy VIKOR) and *A_{10} FOU: Cut with diamond wire saw* (rank 7 with fuzzy TOPSIS, rank 2 with fuzzy VIKOR). A_9 is better with fuzzy TOPSIS, as it is closer to the FPIS (d^*) and further from the FNIS (d^-) (Table SI-2 in the supporting information of publication IX). With fuzzy VIKOR A_{10} is the better alternative, as it is closer to the ideal solution (S_j) (Table SI-4 in the supporting information of publication IX). This is due to the contribution of the weighted normalized fuzzy difference ($w_i * p_{ij}$) of the decision criterion *hazards* (Table SI-3 in the supporting information of publication IX). The ratings of A_9 are much further apart from the ideal solution than A_{10} and this difference is amplified by the high criterion weight' (publication X).

A high correlation in the ranking of the decommissioning alternatives with the different MCDA methods was also found, if the decision criteria are overweighted, i.e., if one of the criteria receives a much higher weight than the other criteria (publication X). The overweighting of the decision criterion *resource efficiency*, however, resulted in very different ranking of the alternatives *A_6 SPL left in situ* and *A_8 WTG-FOU: Cut above seabed.* With fuzzy SAW and fuzzy TOPSIS they received rank 2 and 1. With fuzzy VIKOR and WSM these alternatives are on ranks 9 and 10. 'Intuitively, one could agree with these decommissioning alternatives being ranked lowest, as they have the lowest recycling rates. This is in line with fuzzy VIKOR, where lower recycling rates compared to other alternatives result in larger distances from the best alternatives (Table SI-3 of publication IX). This effect gets amplified by the overweighting of the decision criterion *resource efficiency*.` (publication X) With the WSM, A_6 and A_8 receive very few points for the criteria fulfillment and, consequently, much lower decision scores than the other alternatives. With fuzzy TOPSIS, however, 'even though the differences to the FNIS ($d(v_{ij}, v_j^-)$) for *resource efficiency* of A_6 and A_8 are lower than the other alternatives and despite the overweighting of this criterion, $\mathrm{d}(\mathrm{v_{ij}}, \mathrm{v_j^*})$ is just too small to alter the ranking` (publication X). With fuzzy SAW, $d(f_{ij})$ `values of *resource efficiency* have the greatest contribution to V_i, but just like the V_i values themselves, they lay in very close proximity, so that the values for A_6 and A_8 are only slightly lower than the $d(f_{ij})$ values of *resource efficiency* of the other alternatives. So, the summed impact of $d(f_{ij})$ for *costs*, *GHG emissions* and *biodiversity* which are higher for A_6 and A_8 than for the other alternatives, result in higher preference values V_i` (publication X).

Polatidis et al. (2006) point out 'there are no better or worse techniques, only techniques that fit better to a certain situation or not'. As the fuzzy MCDA methods were selected following the procedure of Wątróbski et al. (2019), it can be assumed that the methods applied should generally be suitable. This study, however, shows that, 'the MCDA methods respond differently to small deviations in the fuzzy ratings. If it is desired, that the method is sensitive to small differences in the (fuzzy) rating, fuzzy VIKOR and the WSM are the methods of choice. With the intention that such small differences should not be decisive for the overall ranking, fuzzy SAW or fuzzy TOPSIS should be applied' (publication X). It should, however, be remembered, that MCDA is a tool to support decision-makers at making decisions and cannot take the responsibility from them. The decision makers still need to critically assess the outcome.

This study shows, that MCDA is a valuable decision-making support tool, as the decision maker (1) is getting familiar with the decision problem in a structured way and (2) obtains in-depth understanding of the processes of the alternatives (this is of special value for unknown processes, that have not been carried out before just as OWF decommissioning). (3) The alternatives are ranked, in this case, with partial decommissioning alternatives often on the highest ranks and feeder concepts on the lowest ranks. (4) All the methods can be easily adjusted and extended with respect to other alternatives and/or decision criteria, which enables a flexible respond to changing conditions and innovative concepts and technologies. This is particularly beneficial, once a baseline has been established to which novel alternatives can be easily compared.

4.1.2 Decommissioning alternatives

In this chapter the ten decommissioning alternatives investigated in this study are discussed with regards to their *Greenhouse gas (GHG) emissions*, *resource efficiency*, impact on epibenthic macrofauna *biodiversity*, *costs* and *hazards*.

Partial decommissioning

In the majority of the analyses, partial decommissioning alternatives occupy the highest ranks (publications VIII, IX and X). With all methods and the different weighting approaches, it is decommissioning alternative *A_6 SPL left in situ*, *A_7 Sea cables left in situ* or *A_8 WTG- FOU: Cut above seabed* that holds the first rank (Table 3 in publication X). The decisive aspect in alternatives A_6 and A_8 is that the scour protection layer is not removed. This is of special relevance for the decision criterion *biodiversity*; only if the scour protection layer was left in situ, the epibenthic macrofauna species richness could be maintained (Table 4 in publication IX, publication VII). Cutting the foundation structure above seabed would add only little value to maintaining epibenthic macrofauna biodiversity. Also, neither the multi-purpose vessel, cargo barge nor rehandling excavator are required to carry out the dredging activities. This results in reduced *costs* and *GHG emissions*, when compared to other alternatives where the scour protection layer is removed (Table 4 in publication IX). In terms of occupational safety, the hazard measure is either equivalent (mean hazard measure of A_6: 930.99) to the baseline scenario A_1 or just slightly lower (mean hazard measure of A_8: 926.65) (Table 4 in publication IX). The recovery rates are even lowest for these decommissioning scenarios (mean recovery rates of A_6: 96.5% and of A_8: 96.4%, publication VIII Table 53). The low recovery rates result from the fact that materials with very high material recovery rates (material recovery rate of stone and steel: 99%) remain offshore and are not fed to waste recycling (Table 51 in publication VIII).

Decommissioning alternative *A_7 = Sea cables left in situ* has the highest recovery rate (98.7%, Table 53 in publication VIII) which can be deduced to the comparable low material recovery rate (95%, Table 51 in publication VIII) of the copper of the sea cables that remains at sea. In terms of *costs* and *GHG emissions*, this alternative is not very favourable (Table 4 in publication IX), as a jack-up vessel and a walk-to-work vessel are required to cut and flush the cables near the turbines. Additionally, these activities actually result in longer process durations than the complete removal of the cables (Table 39 in Eckardt et al. (2022)). For this decommissioning alternative, it is the decision criterion *hazards* that makes the difference. The removal of the cables is associated with activities with high hazard potentials. If the cables were left in situ, the duration of these activities and, hence, the overall hazard measure would be reduced considerably.

Alternative dismantling technologies

Two alternative dismantling technologies were investigated. *A_9 WTG-FOU: Complete removal* where the entire monopile is vibrated out of the seabed with a vibrotool. With alternative *A_{10} FOU: Cut with diamond wire saw* the structures are cut with a diamond wire saw from the outside, instead of cutting the monopile with abrasive water jet cutting from the inside (Eckardt et al., 2022).

Decommissioning alternative A_9 ranges from rank 3 to 8 and A_{10} from rank 2 to 8 (Table 2 in publication X). So, the MCDA methods yield inconclusive results. In terms of duration, *GHG emissions*, *resource efficiency* and impact on the local *biodiversity* both alternatives A_9 and A_{10} do not or only hardly differ from the baseline scenario A_1 (duration (median): A_1 = 4.0 days per location, A_9 = 4.1 days per location, A_{10} = 4.7 days per location; *GHG emissions* (mean CO_2 equivalents): 43.860 t per A_1, 40.712 t per A_9, 44.235 t per A_{10}; *resource efficiency*: A_1 and A_{10} = 98.52%, A_9 = 98.56% and *biodiversity*: A_1, A_9 and A_{10} = 0.00 fraction of species maintained (Table 44 in Eckardt et al. (2022), Table 64 in publication IX). Both alternative dismantling technologies are, however, more expensive than cutting with abrasive water jet cutting method. The costs of using the vibrotool are about 250.000 € per location higher than in A_1 and for cutting with a diamond wire saw the costs are even almost 500.000 € higher (Eckardt et al., 2022 Table 44). From a safety-at-work perspective the alternative dismantling technologies also differ from A_1. While A_9 is the alternative with the second highest hazard measure, A_{10} is the alternative with the second lowest hazard measure (Table 4 in publication IX). Putting the monopile in vibration and lifting it out of the seabed in one piece is associated with a higher risk, than cutting the monopile with abrasive water jetting. Still, if the monopile is cut from the inside, the transition piece needs to be prepared, e.g., removing of internal structures, to allow access of the cutting device. This is associated with risk to personnel. If the monopile was cut with a diamond wire saw from the outside, the human-related preparatory work on the transition piece would be omitted and the cutting device would be attached by an ROV (remotely operated vehicle), resulting in a lower hazard measure. (Ebojie, 2021)

Alternative logistical concepts

Four alternatives in logistics were investigated; three feeder concepts for the transportation of the wind turbine and/or foundation structure to the harbour (A_2 = *Feeder concept: WTG*, A_3 = *Feeder concept: WTG-FOU* and A_4 = *Feeder concept: WTG und WTG-FOU*) and one alternative for the load-off of the offshore substation at the harbour (A_5 = *Load-off offshore substation with SPMT*). Akin to the shuttle concept, with the feeder concepts, the wind turbines and foundation structures are dismantled by a jack-up barge. But instead of shuttling to the harbour, the jack-up vessel loads the components on deck carriers, remains at sea and continues dismantling. The barges transport the components to shore.

Consistently, all feeder concepts (A_2, A_3 and A_4) are ranked lowest (ranks 6 to 10) with all MCDA methods and criteria weighting approaches (Table 2 in publication X). Likewise consistent, alternative A_5 receives primarily rank 4 or 5 (Table 2 in publication X).

All decommissioning alternatives considering variations in logistical concept do not differ from the baseline scenario in terms of *resource efficiency* and impact on *biodiversity* (Table 4 in publication IX). Unloading the offshore substation with SPMT instead of using the crane of the vessel, does not result in any noticeable differences in decommissioning *costs*, *GHG emissions* and *hazards* when compared to A_1 (Table 4 in publication IX). So, if the basic requirements (e.g., tide-independent roll-on/roll-off quay or an adequate ballasting system of the barge) are fulfilled, there is no need for the crane vessel to return to the harbour.

The feeder concepts, however, are associated with considerably higher decommissioning *costs*, *GHG emissions* and *hazards* than the shuttle concept. Decommissioning alternative A_4 even has the highest values in these decision criteria. The high *costs* and *GHG emissions* results from the additional vessels. Next to the jack-up vessel, two deck carrier shuttle between the OWF and harbour to transport the wind turbine and its foundation structure. As the deck capacity of the deck carriers is lower than of the jack-up vessel, the deck carrier can load fewer components, and, consequently, more transits are required. So, the additional vessels and transits results in higher *costs* and *GHG emissions*. The feeder concepts are also associated with a higher hazard measure, which results from the additional lift of components from the static jack-up vessel to the dynamic deck carrier.

4.1.3 Assessment of sustainability

Due to the consideration of multiple and even conflicting objectives MCDA is a powerful tool to assess sustainability. One of the great advantages of MCDA is the transformation of the criteria to dimensionless entities, thereby omitting the units of the attributes and allowing for comparison of decision criteria that would otherwise be challenging to compare. MCDA is, thus, ideally suited for the assessment of sustainability.

Suitability of decision criteria

The selection of suitable decision criteria is case specific, depending on the decision problem itself. However, if the sustainability is to be assessed, at least one criterion of each of the three pillars of sustainability, namely environmental, economic and social, should be selected. For the case study, initially, seven decision criteria were preselected and evaluated at a workshop with about 60 experts from different disciplines of the OWF industry (publication IV). In the course of the *SeeOff* research projects, the decision criteria were narrowed down to three environmental (*GHG emissions*, *resource efficiency* and *biodiversity*), one social (*hazards*) and one economic (*costs*) decision criteria due to time and manpower constraints (publications VIII). The triple amounts of environmental criteria might seem like an imbalance. But, for one thing, the reduction of *GHG emissions* (United Nations, 2015a), the improvement of *resource efficiency* (European Union, 2018) and the conservation of biological *biodiversity* (United Nations, 1992, 2010) are pressing topics of international relevance. By considering these aspects, OWF decommissioning can contribute to the United Nations Sustainable Development

Goals 12 ‘Ensure sustainable consumption and production patterns’, 13 ‘Take urgent action to combat climate change and its impacts’ and 14 ‘Conserve and sustainably use the oceans, seas and marine resources for sustainable development’ (United Nations, 2015b) (publication IV). Secondly, all decision criteria considered for OWF decommissioning were presented to and discussed with an audience of about 60 experts of different disciplines related to offshore wind energy at a workshop. All decision criteria have been met with approval. Subsequently, the selected decision criteria were weighted by pairwise comparison as part of an online survey by 76 participants of the OWF industry. This revealed, that even if being less important than the decision criterion *hazards*, all of the environmental aspects were more relevant than the decommissioning *costs*.

The investigation of the decision criteria has revealed, that the offshore vessels are the major drivers for both, *costs* and *GHG emissions*. There is, thus, a dependency of these two decision criteria (publication X). Even though decision criteria should ideally be independent from each other, this is often challenging to comply with in reality (Geldermann & Lerche, 2014). With the superior target to assess the sustainability of OWF decommissioning, neither criterion can be simply dispensed. Actually, this emphasises that decommissioning alternatives with reduced utilization of vessels benefit the reduction of both, *costs* and *GHG emissions*.

Four of these decision criteria have proven to be suitable to assess the sustainability of OWF decommissioning: *GHG emissions*, *costs, biodiversity* and *hazards* (publications VIII and IX). The attribute recycling rate of the decision criterion *resource efficiency*, however, has turned out to not be suitable to assess partial decommissioning. ‘Wind turbines and their monopile foundation structures consist to a large proportion of steel, which has a material recovery rate of 99%. Therefore, these components have a high recovery rate of 94.5 and 99%, respectively (see table 26, 51 and 53 in Eckardt et al. (2022)). Sea cables are made up of materials that have a lower material recovery rate (e.g., insulation, bedding or serving), which reduces the recovery rate of sea cables to 88.4% (see tables 26, 51 and 53 in Eckardt et al. (2022)). If sea cables remain at sea, a large quantity of materials with low material recovery rate are not included in the calculation, resulting in a high overall recovery rate. Form a resource efficiency perspective, leaving resources such as copper at sea instead of recycling them, is not preferable. Consequently, if resource efficiency was to be considered when assessing the sustainability of OWF decommissioning, the criterion measure should be selected to account for the amount and types of materials that remain at sea’ (publication IX).

Influence of criteria weights

The decision criteria were weighted by pairwise comparison by 76 participants and mean values with upper and lower 1-$\boldsymbol{\sigma}$-interval were calculated (publication IX). The wide-ranging and overlapping deviances of the criteria weights established in the online survey (Table 1 of publication IX) suggests, that stakeholders rate the relevance of the decision criteria quite differently. To test how the criteria weighting influences the ranking of the decommissioning alternatives, the ranks were recalculated with the four MCDA methods using overweighted decision criteria (publication X).

When calculated with fuzzy SAW and fuzzy TOPSIS, the weighting approach has little influence on the ranking of the decommissioning alternatives (Figure 13 and Figure 14 in publication X). The consistent ranking implies that the rating of the alternatives has a greater influence on the ranking than the weight of the decision criteria. With fuzzy VIKOR and WSM, however, the overweighting of the decision criteria produces variation in the ranking. This is obvious for the ranking with overweighted decision criteria *hazards* and *GHG emissions* and *costs*, respectively, but it is most profound for overweighting of the criterion *resource efficiency,* (Figure 15 and Figure 16 in publication X). This analysis suggests, that fuzzy VIKOR or the WSM should be applied, if the criteria weighting is to be given more credit. Otherwise, variation in the fuzzy ratings appear to have a greater influence on the ranking of the alternatives than the criteria weights.

4.2 Further considerations

4.2.1 Other decommissioning alternatives

In this analysis, ten decommissioning alternatives were investigated considering different dismantling technologies, logistical concepts and scopes of decommissioning. These alternatives were chosen for the reference OWF based on availability of data and information as well as environmental, economic and social selection criteria (publication IX). The investigation of other decommissioning alternatives, especially for different OWF, might be purposeful.

Even though the dismantling technologies were selected to meet the requirements of the reference OWF, some of them might also be applied to structurally differing OWF. E.g., abrasive water jet cutting could also be used for the decommissioning of jackets or the dismantling of gravity-based foundations, however, other equipment is required (publication VIII). With increasing turbine and foundation sizes, the applicability of these dismantling technologies would have to be re-evaluated and adapted, if necessary (publication VIII). Also, with increasing expansion targets, there will probably be a high demand to reuse the OWF areas for new, more powerful OWF. Consequently, the previously installed OWFs might be decommissioned rather soon (opposed to life-time extension). With increasing demand, but also with more experiences, the dismantling technologies are likely to develop over the next years. Novel dismantling equipment might also pose other requirements on the associated logistics. This study shows, that most of the decommissioning *costs* and *GHG emissions* result from offshore vessels. In order to make a considerable contribution to SDG 13: 'Take urgent action to combat climate change and its impacts' (United Nations, 2015b) novel logistical concepts are required. Such innovations should at best reduce or forgo the use of large vessels.

Also, 'dismantling and logistics concepts depend highly on the location of the OWF, including hydrological aspects like water depth and seabed morphology, as well as the distance from and types of harbours' (publication VIII). Although not considered in this study, it is probable, that not a single, but different harbours specialized on processing certain OWP components will be used for OWF decommissioning. There are several factors for the selection of suitable harbour sites, such as bearing pressure or connectivity to recycling facilities. Requirements for harbours, such as bearing capacity, storage facilities or lifting gear, vary widely with the different OWF components e.g., wind turbines, foundation structures or the offshore substation (Elkinton et al., 2014). The connectivity to corresponding recycling facilities might also be a relevant criterion. The reference OWF of this case study consists of more than 50%, i.e., over 115 000 t, stones (scour protection) and over 40%, almost 95 000 t, steel that need to be processed at the harbour. It might be favourable to set up a scrape yard, directly in the harbour. This is, however, at least in Germany, associated with a complex and time-consuming approval process according to the German Federal Immission Control Act. But also, the connectivity to other recycling facilities, such as for the rotor blades, might be decisive for the harbour selection.

Concerning the scope of decommissioning, partial decommissioning such as 'topping', where parts or the complete structures are placed on the seabed as suggested by Fowler et al. (2019), are unlikely for OWF in the North Sea. But other concepts of partial decommissioning might be subject to further investigation. For example, leaving parts of the foundation structures, particularly the scour protection, not of all, but only of a couple of locations that uphold connectivity and act as sources for subsequent colonisation. This might be of particular interest of areas where new OWF will be installed.

4.2.2 Subsequent use of the offshore wind farm area

German regulations require that OWF are to be dismantled so that they do not pose any hazard to the safety and efficiency of traffic (publication II). If structures were not removed completely, they might pose a hazard, e.g., if trawl nets become entangled and cause fishing vessels to capsize (publication II). Whether, and if so, to what extend components such as scour protection, inner-array cables or foundation structures cut above sea bed that are left in situ, actually would be a hazard to the safety and efficiency of traffic, could not be resolved in this study and requires further investigations.

With increasing expansion targets for offshore wind energy, the reuse of the OWF areas is gaining more and more attention. Within the Ostend declaration of Energy Ministers on the North Sea as Europe's green power plant on 24.04.2023 nine European countries set the ambitious target to increase energy generated by offshore wind to at least 120 GW by 2030 and 300 GW by 2050. The three leading countries are the United Kingdom that aims for 50 GW to be installed by 2030, Germany for 26.4 GW and the Netherlands for 21 GW. Partial decommissioning should not hinder these targets. While remaining scour protection is believed to not be an obstacle for the installation of new wind turbines, inner-array cables that are left in situ would most likely interfere with the installation of new cables (publication VIII). In how far partial decommissioning would be an obstacle for the reuse of the OWF area remains to be investigated in detail.

The previously installed foundation structures also need to be taken into consideration when planning a new OWF, albeit the layout will differ due to larger, but fewer wind turbines. Irrespective of whether the foundation structures are cut below or above seabed, the installation of new foundation structures at the same location is believed not to be possible. The same is probably true for the complete removal with a vibrotool, where the seabed is put into a pseudo-liquid state so that the monopile can be pulled out. In how far this procedure changes the seabed conditions so that the installation of new foundation structures at or near the same location is impaired, requires further investigations. (publication VIII)

4.2.3 Other decision criteria for the assessment of sustainability

Decision criteria are always case-specific and should be defined in consultation with the relevant stakeholders (publication IV). In this study five decision criteria were selected for the assessment of the sustainability of OWF decommissioning. Other decision criteria, however, could also be considered.

A further environmental decision criterion could be *ecosystem services* with the objective that OWF decommissioning should have only minor impact on the local biomass of commercial species (publication IV). Foundation structures and particularly the scour protection provide shelter as well as feeding and nursing grounds for commercial benthic species like the edible crab (*Cancer pagurus*) or fish species such as the atlantic cod (*Gadus morhua*) or the pelagic horse mackerel (*Trachurus trachurus*) as indicated by an increase in abundance (Coolen et al., 2019; Krone et al., 2017; Reubens et al., 2013; Stenberg et al., 2015; van Hal et al., 2017). By maintaining habitat for commercial species OWF decommissioning could contribute to the United Nations SDG 14: 'Conserve and sustainably use the oceans, seas and marine resources for sustainable Development' (United Nations, 2015b).

As suggested in publication IV *public acceptance* could also be a decision criterion worth to consider in a MCDA. Large-scale projects have the potential to receive considerable public attention. In Germany it is planned that foundation structures are cut below seabed with the bottom part remaining in the seabed (publication II). Some might argue, that the operators just leave their waste at sea. Assessing the public attitude towards e.g., partial decommissioning or novel decommissioning technologies, enables the identification of potential pitfalls. Subsequently, the public can be informed about the dismantling plans and their potential impacts and, thereby, counteract misconception and possible trouble with potential opponents.

4.2.4 Improvement of data and knowledge basis

This study emphasizes the demand for a well-founded knowledge and data basis (publications VII, VIII and IX). Due to the lack of experiences, there are no best practices and the processes underlying the decommissioning alternatives are based on literature research and experts' opinions (Eckardt et al., 2022). These experts were not always in complete agreement, e.g., there were different opinions on the feasibility of the feeder concepts. Having a heterogeneous group of specialists debating on decommissioning alternatives considerably contributes to consider a large number of advantages, disadvantages, consequences and potential obstacles but also to bring forward solutions and innovative ideas. Akin, a lot of the data, e.g., process durations, for calculating the criteria values derive from experts' estimates. This results in a lot of uncertainty, which was faced with the application of fuzzy MCDA in publications IX and X. An improvement of the data and knowledge base would considerably contribute to reducing this uncertainty. For some of the data, such as process duration, a reduction of uncertainty is challenging, as the uncertainty arises from unknown processes (i). The quality of decision criteria could be improved, if confidential data was made public, e.g., fuel consumption of vessels or material composition of manufacturers (ii). Other data, then again, does not even exist in sufficient quality and quantity and have yet to be collected (iii).

(i) Process durations are required to calculate decommissioning *costs*, *GHG emissions* and *hazard measure*. Obtaining exact process durations is very challenging. There is too little experience and many activities, such as complete removal of monopiles with a vibrotool, have not been carried out before at all. Also, offshore activities are associated with unpredictable events or bad weather resulting in delays. Good approximations will probably be obtained from a heterogenous group of well-experienced experts.

(ii) As illustrated in Figure 77 in publication VIII CO_2-equivalents primarily result from processes at sea, i.e., the vessels. The fuel consumptions were estimated based on the vessel specific propulsion power, the loading (design displacement) and the transition speed (publication VIII). For more reliable calculations, the actual fuel consumptions of the vessel while performing the different activities, e.g., transit, dismantling or standby, are required. Such information exists, is, however, usually confidential. The same applies to the calculation of the recycling rate. The mass balance of the materials of the reference OWF (Table 26 is publication III) is based on the estimation of a waste management expert. Detailed information of the manufacturers, would, of course, improve the mass balance of the OWF considerably, is, however, confidential as well.

(iii) For other data, then again, it is rather a matter of collection. As outlined in publication V, there is a great demand on monitoring data to assess impacts of decommissioning on the marine environment. E.g., targeted investigations on the growth and demersal megafauna at the scour protection layer and the bottom of the foundation, the surrounding soft-bottom and fish communities, species of commercial and conservational interest, overall food-web and connectivity of communities over the entire or at least towards the end of the operational life-time of the OWF turbines. Such investigations are, however, not planned for Germany (publication VII).

4.2.5 Further research

This thesis demonstrates, how MCDA can be applied for the assessment of the sustainability of OWF decommissioning. But it also revealed potential for improvement and demand for further research. This study suggests to

- reduce or even forego the usage of large vessels to reduce costs and GHG emissions,
- leave scour protection in situ to maintain benthic biodiversity and
- improve data and knowledge base to improve the assessment of decommissioning alternatives.

Future research should, hence, focus on decommissioning concepts, dismantling technologies and/or associated investigations, that consider these aspects. So, cost-effective and environmental-friendly logistical concepts should be taken into consideration, when improving or developing dismantling technologies, e.g., for larger turbines and foundation structures.

For the investigation of partial decommissioning concepts, special focus should be laid on resolving in how far components such as scour protection or foundation structures cut above seabed that were left in situ, actually would be a hazard to the safety and efficiency of traffic. Also, the reuse of the OWF area should be taken into consideration, especially with regards of erecting of new wind farms in the same area.

As long as no knowledge is available, good approximations to deepen understanding of decommissioning processes will probably be obtained from a heterogenous group of well-experienced experts. However, sharing of confidential data, such as vessel fuel consumptions or material composition of the components, would considerably contribute to improving the data base for the assessment of the decommissioning alternatives. Last but not least, the collection of data such as environmental monitoring data, is essential in order to have a basis at all for the evaluation of decommissioning alternatives and the decision-making process.

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