



## **DELIVERABLE 4.4**

# **ENVIRONMENTAL IMPACT ASSESSMENT MODEL FOR THE COMMERCIAL ROLLOUT OF MULTI-USE PLATFORMS**

Work Package 4

Environmental added-value of multi-use of marine space and infrastructure

8 September 2023





Funded by the European Union (H2020 Grant Agreement no 862915). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them



<b>Grant number</b>	<b>Agreement</b>	<b>862915</b>
<b>Project title</b>	<b>UNITED: multi-Use platforms and co-location pilots boostIng cost-effecTive, and Eco-friendly and sus-tainable proDuction in marine environments</b>	
<b>Deliverable title</b>	Environmental impact assessment models for the commercial rollout of Multi-Use Platforms	
<b>Deliverable number</b>	4.4	
<b>Deliverable version</b>	Original Submission	
<b>Contractual date of delivery</b>	December 31 <sup>th</sup> , 2022	
<b>Actual date of delivery</b>	September 8 <sup>th</sup> , 2023	
<b>Document status</b>	Review for Submission	
<b>Document version</b>	Version 1	
<b>Online access</b>	No	
<b>Diffusion</b>	Private	
<b>Nature of deliverable</b>	Other	
<b>Work Package</b>	WP4 – Environmental added-value of multi-use of marine space and infrastructure	
<b>Partner responsible</b>	RBINS	
<b>Contributing Partners</b>	WUR	
<b>Author(s)</b>	Annaïk Van Gerven, Marcel J.C. Rozemeijer, Ruud Jongbloed, Jacqueline Tamis, Tasnim Patel, Thomas Kerkhove, Steven Degraer, Gerjan Piet.	
<b>Editor</b>	Tim Staufenberger, Roderik Hoekstra, Ivana Lukic, Mariana Mata Lara	
<b>Abstract</b>	The assessment of environmental impact of multi-use projects can be done following the UNITED Assessment Framework (UAF) five steps. The UAF is a framework conceived in the Horizon 2020 European UNITED project, inspired by a classic EIA approach, as a method for assessing impact of ocean multi-use. As part of task 4.4 of UNITED, “Development of environmental impact assessment models for commercial rollout of multi-use”, steps 1 and 2 of the UAF were achieved at least partially. To achieve step 1, scoping of impact and identification of key impacts, a cumulative impact assessment	

(CIA) methodology was applied to the upscaled commercial projections of the five pilots of UNITED. These impacts were then predicted with the same tool, then further developed into wider consequences and potential benefits (added-value of multi-use) on the marine environment, with a qualitative assessment based on literature review, experience from the pilots and expert judgement.

As part of the CIA, activities in the upscaled projections of the pilots were described based on three phases: installation, operation and decommissioning. All activities were decomposed into actions, then linked to pressures and ecosystem components, as prescribed by the CIA methodology. This analysis was done for a generic baseline scenario, and for a single-use (SU) scenario and a multi-use (MU) scenario for each pilot, allowing for a comparison of impact risk (IR) between SU and MU for each step of each pilot. These pilots should be considered “proof of concept” that if this extended multi-use CIA is able to evaluate a single-use design with that of multi-use it can be considered sufficiently generic to support the commercial rollout of Multi-Use Platforms.

The main findings of this application of the extended CIA in a multi-use EIA context were that considerable negative impact reductions compared to single-use can be achieved through multi-use. Highest reductions of approximately 40% for fish and mammals in the installation phase of the Belgian and Dutch pilots, approximately 15% for fish and mammals in the operation phase of the Dutch pilot and approximately 20% for seabed habitats in the decommissioning phase of the Belgian pilot.

Adapting the CIA to small-scale scenarios proved complex, because the tool was originally designed to assess impacts at a sea-basin level. While great advancements have been made, not all impacts could be accounted for and some wider consequences of multi-use were described in the second part of this report, based on literature review and expert knowledge. The wider expected positive consequences of ocean multi-use projects on the marine environment are: opportunity for habitat restoration; biodiversity increase thanks to strong fisheries exclusions and artificial reef effect; potential increase in commercial fish species; increased nutrient cycling and carbon sequestration; sustainable food production and increased social acceptability towards offshore wind production and aquaculture; more space for conservation and reduction of conflicts over space use at sea.

Within the current context, the extent to which actions from different activities can be combined is limited because of technological and regulatory challenges. Yet, because these limits may be removed in the future, the CIA was applied to a potential optimal scenario in which MU can be exploited to its full potential. This predictive analysis indicate that MU projects could provide substantial impact risk reduction in the future.

In addition, optimization measures were identified to promote environmental benefits identified from the wider consequences of MU projects. These measures specifically target means to render OWF and aquaculture more suitable for multi-use, and to enhance positive impact on the marine environment. These measures are nature-inclusive design of infrastructures at sea, rethinking OWF decommissioning, using an electrical fleet to operate at sea and using biodegradable materials in aquaculture farms.



Funded by the European Union (H2020 Grant Agreement no 862915). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them



<b>Keywords</b>	Ocean multi-use, UNITED Assessment Framework, Environmental Impact Assessment, Cumulative Impact assessment, Artificial reef effect, Offshore wind farms, Aquaculture, Low-trophic aquaculture, Marine tourism
<b>Change Log</b>	Resubmission 1 – change in cover page and introduction tables



---

## TABLE OF CONTENTS

<b>TABLE OF CONTENTS .....</b>	<b>5</b>
<b>ACRONYMES .....</b>	<b>6</b>
<b>EXECUTIVE SUMMARY .....</b>	<b>7</b>
<b>1. INTRODUCTION .....</b>	<b>8</b>
<b>1.1. CONTEXT .....</b>	<b>8</b>
<b>1.2. DESCRIPTION OF UNITED .....</b>	<b>8</b>
<b>1.3. DESCRIPTION OF WP4 AND ITS DELIVERABLES.....</b>	<b>9</b>
<b>1.4. THE UNITED ASSESSMENT FRAMEWORK .....</b>	<b>9</b>
<b>2. CUMULATIVE IMPACT ASSESSMENT OF MULTI-USE .....</b>	<b>12</b>
<b>2.1. THE CIA METHOD .....</b>	<b>12</b>
<b>2.2. RESULTS OF THE CIA.....</b>	<b>21</b>
<b>2.3. EVALUATION OF MULTI-USE .....</b>	<b>34</b>
<b>2.4. CONCLUSIONS AND DISCUSSION ON THE CIA OF MULTI-USE.....</b>	<b>36</b>
<b>3. WIDER CONSEQUENCES OF MULTI-USE .....</b>	<b>37</b>
<b>3.1. METHOD .....</b>	<b>37</b>
<b>3.2. ASSESSMENT .....</b>	<b>38</b>
<b>3.3. DESCRIPTION OF POTENTIAL WIDER CONSEQUENCES .....</b>	<b>38</b>
<b>3.4. CONSIDERATIONS IN DEVELOPMENT AND DESIGN OF OWF FOR MULTI-USE</b>	<b>43</b>
<b>4. CONCLUSIONS .....</b>	<b>46</b>
<b>5. LITERATURE .....</b>	<b>47</b>
<b>ANNEX 1 – DESCRIPTION OF THE PILOTS .....</b>	<b>51</b>
<b>PILOT 1: FINO3 (FUE, GERMANY) .....</b>	<b>51</b>
<b>PILOT 2: NORTH SEA INNOVATION LAB (DEN HAAG, THE NETHERLANDS) .</b>	<b>51</b>
<b>PILOT 3 : INTEGRATION OF NATIVE FLAT OYSTER PRODUCTION, FLAT OYSTER RESTORATION AND SEAWEED CULTIVATION IN AN OFFSHORE WIND FARM (BELGIUM) .....</b>	<b>53</b>
<b>PILOT 4: TOURISM AT MIDDELGRUNDEN WIND (DENMARK) .....</b>	<b>54</b>
<b>PILOT 5: AQUACULTURE/TOURISM (GREECE).....</b>	<b>55</b>
<b>ANNEX 2 – ACTIONS CONSIDERED IN THE UNITED PILOTS.....</b>	<b>57</b>
<b>ANNEX 3 – REPORTED DURATIONS PER PILOT .....</b>	<b>61</b>
<b>ANNEX 4 - DEFINING A POTENTIAL OPTIMAL SCENARIO .....</b>	<b>70</b>

---

## ACRONYMES

CCT	Coordination Committee Team
CIA	Cumulative Impact Assessment
CSET	Core Services Exploitation Team
CT	Consortium Coordination Team
EC	Ecosystem Component
EIA	Environmental Impact Assessment
GES	Good Environmental Status
ICES WGCEAM	Working Group on the use of Cumulative Impact Assessments for Management
IPR	Intellectual Property Right
IR	Impact Risk
LTA	Low-Trophic Aquaculture
MSFD	Marine Strategy Framework Directive
MSP	Maritime Spatial Planning
MU	Multi-Use
OWF	Offshore Wind Farm
PA	Partner Assembly
PAWP	Prinses Amalia Wind Park
PM	Project Management
SAB	Stakeholder Advisory Board
SCAIRM	Spatial Cumulative Assessment of Impact Risk for Management
SU	Single-Use
UAF	UNITED Assessment Framework
WP	Work package

---

## EXECUTIVE SUMMARY

The assessment of environmental impact of multi-use projects can be done following the UNITED Assessment Framework (UAF) five steps. The UAF is a framework conceived in the Horizon 2020 European UNITED project, inspired by a classic EIA approach, as a method for assessing impact of ocean multi-use. As part of task 4.4 of UNITED, “Development of environmental impact assessment models for commercial rollout of multi-use”, steps 1 and 2 of the UAF were achieved at least partially. To achieve step 1, scoping of impact and identification of key impacts, a cumulative impact assessment (CIA) methodology was applied to the upscaled commercial projections of the five pilots of UNITED. These impacts were then predicted with the same tool, then further developed into wider consequences and potential benefits (added-value of multi-use) on the marine environment, with a qualitative assessment based on literature review, experience from the pilots and expert judgement.

As part of the CIA, activities in the upscaled projections of the pilots were described based on three phases: installation, operation and decommissioning. All activities were decomposed into actions, then linked to pressures and ecosystem components, as prescribed by the CIA methodology. This analysis was done for a generic baseline scenario, and for a single-use (SU) scenario and a multi-use (MU) scenario for each pilot, allowing for a comparison of impact risk (IR) between SU and MU for each step of each pilot. These pilots should be considered “proof of concept” that if this extended multi-use CIA is able to evaluate a single-use design with that of multi-use it can be considered sufficiently generic to support the commercial rollout of Multi-Use Platforms.

The main findings of this application of the extended CIA in a multi-use EIA context were that considerable negative impact reductions compared to single-use can be achieved through multi-use. Highest reductions of approximately 40% for fish and mammals in the installation phase of the Belgian and Dutch pilots, approximately 15% for fish and mammals in the operation phase of the Dutch pilot and approximately 20% for seabed habitats in the decommissioning phase of the Belgian pilot.

Adapting the CIA to small-scale scenarios proved complex, because the tool was originally designed to assess impacts at a sea-basin level. While great advancements have been made, not all impacts could be accounted for and some wider consequences of multi-use were described in the second part of this report, based on literature review and expert knowledge. The wider expected positive consequences of ocean multi-use projects on the marine environment are: opportunity for habitat restoration; biodiversity increase thanks to strong fisheries exclusions and artificial reef effect; potential increase in commercial fish species; increased nutrient cycling and carbon sequestration; sustainable food production and increased social acceptability towards offshore wind production and aquaculture; more space for conservation and reduction of conflicts over space use at sea.

Within the current context, the extent to which actions from different activities can be combined is limited because of technological and regulatory challenges. Yet, because these limits may be removed in the future, the CIA was applied to a potential optimal scenario in which MU can be exploited to its full potential. This predictive analysis indicate that MU projects could provide substantial impact risk reduction in the future.

In addition, optimization measures were identified to promote environmental benefits identified from the wider consequences of MU projects. These measures specifically target means to render OWF and aquaculture more suitable for multi-use, and to enhance positive impact on the marine environment. These measures are nature-inclusive design of infrastructures at sea, rethinking OWF decommissioning, using an electrical fleet to operate at sea and using biodegradable materials in aquaculture farms.

---

## 1. INTRODUCTION

### 1.1. Context

Ocean multi-use (MU) is the practice of integrating multiple activities and functions in a given ocean space to optimize the benefits of ocean resources while minimizing negative impacts on the environment. This approach recognizes that the ocean can offer various benefits, including food, energy, transport, recreation, and biodiversity conservation, which can be optimized through strategic planning and management.

Examples of ocean multi-use activities include offshore wind farms (OWF) and aquaculture, marine protected areas and tourism, desalination plants and renewable energy, and offshore oil and gas development and fishing. By integrating multiple activities, ocean multi-use can help reduce conflicts between ocean users and promote sustainable and efficient use of ocean resources.

Ocean multi-use can provide economic opportunities by allowing multiple activities to take place in the same area, improving resource efficiency, enhancing environmental protection, contributing to climate change mitigation, and improving social benefits, such as creating new job opportunities and promoting collaboration between different ocean users. However, successful implementation requires careful planning and management to ensure compatibility and minimize negative impacts on the environment and other users. Overall, ocean multi-use has the potential to promote sustainable and integrated use of ocean resources and create economic, environmental, and social benefits.

Despite the growing attention on ocean multi-use, concrete implementation remains rare. As part of this project, the potential for ocean multi-use was explored in the North Sea with four pilots, and in the Mediterranean Sea with one pilot. Both seas present interesting opportunities for multi-use and potential environmental, social and/or economic benefits (Bocci, Remier et al., 2017). Examples of activities that could be combined are offshore renewable energy production, aquaculture, conservation and restoration, marine protected areas, tourism (boat tours, diving tours, etc.). Adopting an integrated approach to ocean use can provide economic, environmental, and social benefits, including new economic opportunities, improved resource efficiency, enhanced environmental protection, and more sustainable and equitable ocean governance.

### 1.2. Description of UNITED

The H2020 programme UNITED provides pilot results and research for the EU topic of interest “BG-05-2019 Multi-use of the marine space, offshore and near-shore: pilot demonstrators”<sup>1</sup>. The objective of the H2020 UNITED project is to encourage multi-use of marine areas by developing guidelines, tools and experience through five pilots. These pilots combine renewable energy, aquaculture, nature restoration and tourism activities, with the aim to provide evidence for the viability of marine multi-use. UNITED will provide solutions to improve operation, planning, and management of multiple marine offshore activities, as well as reducing costs and space demand of offshore operations.

The project is deployed across five pillars, presenting challenges and opportunities:

- Technological;
- Economic;
- Environmental;
- Societal;
- Legal/Policy/Governance.

The five developed pilots combine the following activities:

- German pilot: offshore wind research and aquaculture (mussels and seaweed);
- Dutch pilot: offshore wind, floating solar energy research and aquaculture (seaweed);

---

<sup>1</sup> BG-05-2019: Multi-use of the marine space, offshore and near-shore: pilot demonstrators | Atlantic Action Plan | Atlantic Strategy (europa.eu)

- Belgian pilot: offshore wind, aquaculture (European flat oysters and seaweed) and oyster reef restoration;
- Danish pilot: offshore wind and tourism;
- Greek pilot: aquaculture (finfish) and tourism.

### 1.3. Description of WP4 and its deliverables

WP4 of UNITED aims to determine what the added value of the multi-use of marine space and infrastructure could be from an environmental perspective. It represents the environmental pillar of the project and addresses current knowledge gaps on the measurement and assessment of cumulative environmental impacts of marine multi-use. The first deliverable of WP4, “Deliverable 4.1. Revision of the current environmental assessment and status of pilots”, synthesised the environmental practices, requirements, and available environmental information for the five pilots to establish the initial baseline and identify information gaps. The second deliverable, “Deliverable 4.2. Assessment framework to determine ecological feasibility of multi-use platforms”, proposed the Cumulative Impact Assessment (CIA) approach as a tool to assess the environmental impact of multi-use projects. The third deliverable, “Deliverable 4.3. Application of assessment framework within pilots”, applied the CIA approach to the single-use scenario, and the present deliverable, D4.4, applies this approach to the multi-use scenarios of the upscaled projections of the UNITED pilots.

This deliverable reports on task 4.4. “Development of environmental impact assessment models for the commercial rollout of Multi-Use Platforms”. In addition to the CIA, potential benefits and wider consequences of multi-use projects are investigated, as a mean to assess the meaningfulness of the environmental added value of multi-use (MU)

### 1.4. The UNITED Assessment Framework

To assess environmental impact of ocean multi-use, the generic model proposed is the UNITED Assessment Framework (UAF), schematized in Figure 1. Kerkhove *et al.* (to be published) describes the UAF in detail.

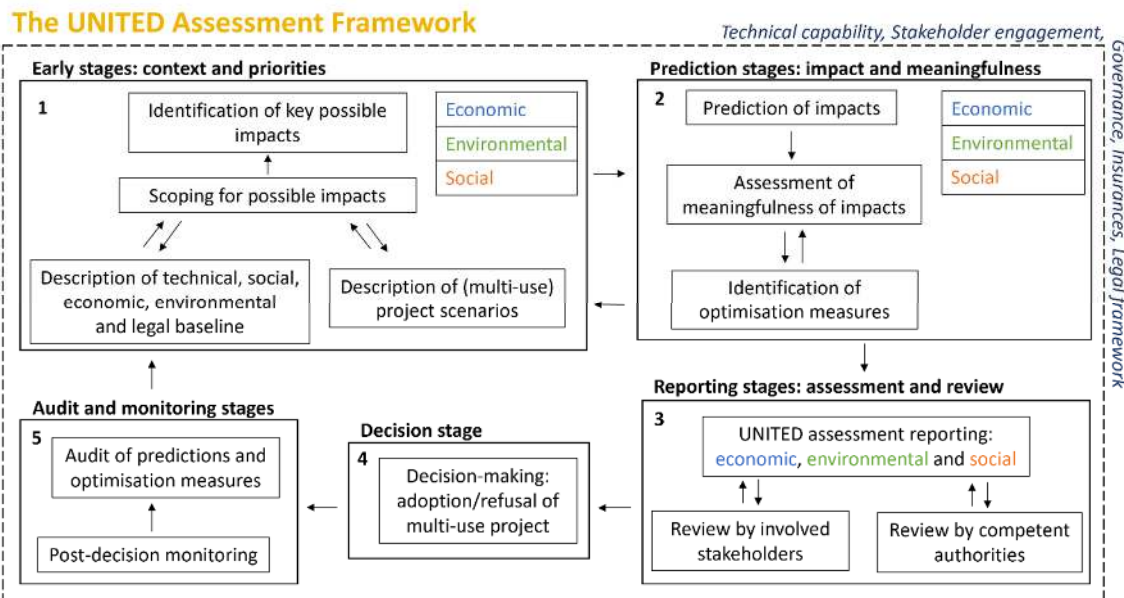


Figure 1. The UNITED Assessment Framework.

The first step of the UAF is the description of the baseline, which is reported in deliverable 4.1, and the description of scenarios, as illustrated in Figure 2. In the context of UNITED, the envisaged scenarios are the following: a baseline scenario with none of the considered activities happening at all, which is described in the first section of this report; single uses scenarios where each activity happens but without any interactions or sharing of space nor infrastructure; a multi-use scenario where the considered activities share space and/or infrastructure.

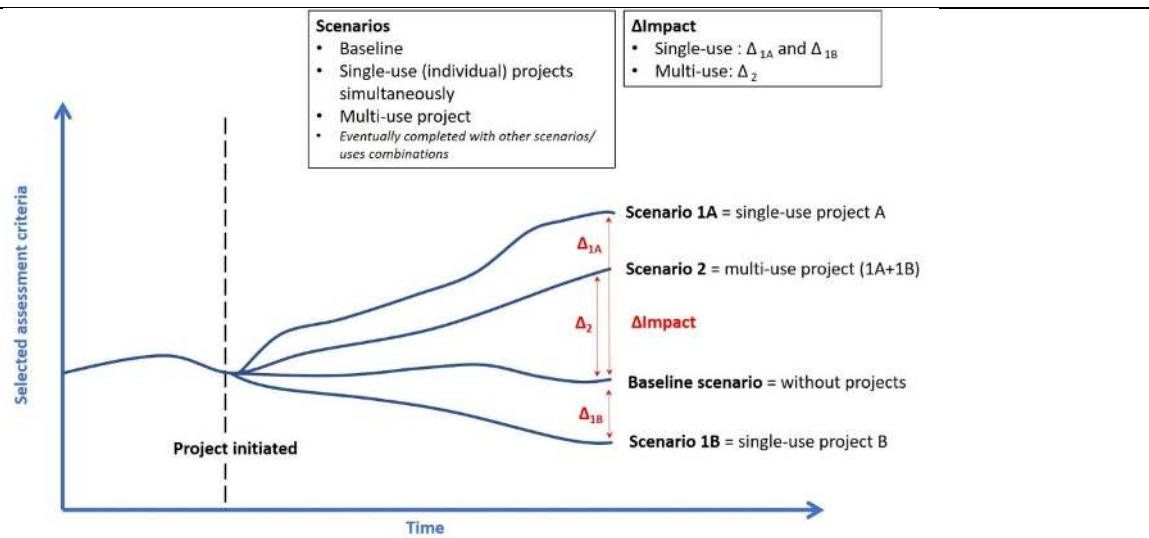


Figure 2. Changes in impact ( $\Delta$ Impact) for selected assessment criteria (Y-axis) over time (X-axis) between different scenarios, (WPA concept paper Kerkhove et al., 2020, and adapted from Glasson et al. 2005).

Stages 1 and 2 of the UAF were addressed with a cumulative impact assessment tool, hereafter referred to as CIA. As illustrated in Figure 3, scoping for possible impacts and identification of key impacts were achieved, in the context of the CIA, when linking activities, further detailed into actions, to pressures. The following steps of the UAF, in box 2, predicting impacts and assess meaningfulness of impacts was done by the CIA when linking pressures to ecosystem components.

## Implementation of the UAF: environmental assessment

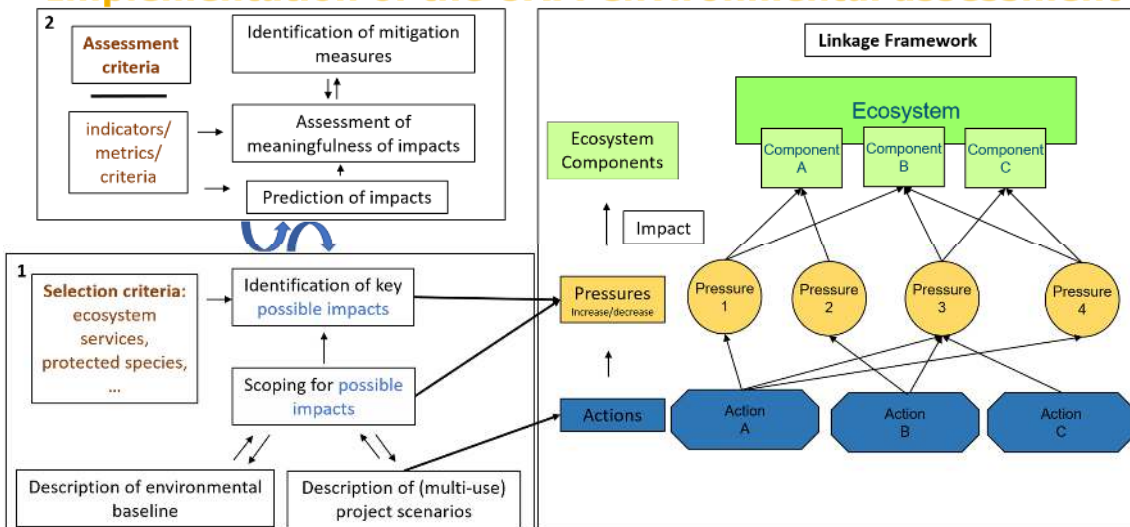


Figure 3. Positioning the Cumulative Impact Assessment (CIA) approach in relation to Box 1 and 2 of the UNITED Assessment Framework.

The assessment of the meaningfulness of the impacts can be different things. It can be looking at the magnitude of pressures and the sensitivity of the ecosystem components, as is done by the CIA. Or it could be looking at the broader context and assessing which impact is the most significant, as was done by the second section of this report, which focuses on wider consequences of ocean multi-use. Other ways to assess the meaningfulness of impacts can be envisaged, what is reported in this deliverable is one example of the application of the UAF. Finally, the last part



---

of the second step of the UAF, the identification of mitigation measures is developed in the second section of this deliverable, with suggestions of optimization measures for potential benefits. If the analysis had focused on negative impacts, mitigation measures would have been developed.

The CIA is a method originally designed to be applied to a larger scale, at a basin or sea scale. Applying it at the scale of a wind farm or a finfish farm presented challenges and required substantial adaptation that is described in the method section of the CIA. While great progress was achieved, some aspects could not be fully covered, such as the integration of potential benefits for the environment, and the CIA being originally conceived to assess negative impact. Indirect impacts also had to be overlooked by the methodology, because of lack of data and the high level of complexity that was required to add a step to the linkage framework. Since several potential benefits were indirect ones, these were incorporated into the second part of the impact assessment, which looks at wider consequences of multi-use and at the meaningfulness of these wider consequences, fitting into the second step of the UAF. Finally, a certain level of detail could not be achieved by the CIA at this stage, that is to assess impacts at species or specific habitats level. The CIA was designed to assess the impact on certain ecosystem components, and this could not be changed within the scope of the UNITED project.

To complement the CIA in achieving steps 1 and 2 of the UAF, and because the work package focuses on added-value of multi-use, the meaningfulness of wider consequences of ocean multi-use was assessed with a table looking at what the contribution is on the ecosystem health, what European environmental goals and strategies could benefit from multi-use projects, and what ecosystem services would be provided by the identified wider consequences. A similar exercise could be done looking at wider negative consequences of ocean multi-use projects such as the risk of increases CO<sub>2</sub> emission caused by increased boat use, but it fell out of the scope of this deliverable and WP.

Of the remaining steps 3 and 5 are reported upon in work package 8 “Assessment and Validation”, deliverable 8.3. “Report on environmental assessment and validation” being the environmental assessment report and deliverable 8.4 “UNITED auditing procedures and TRL assessment manual” proposing a guide for environmental audit of ocean multi-use projects.

## 2. CUMULATIVE IMPACT ASSESSMENT OF MULTI-USE

### 2.1. The CIA method

A CIA method is a systematic procedure to identify and assess environmental impacts caused by multiple sources or activities, through a linkage framework. The result is an overview of the combined effects of the considered activities, taking into account positive/negative and direct impacts. This overall view of estimated impacts provides a way to compare different scenarios, select the best option, and implement efficient management measures.

The analysis of the causes (source of pressures and effects), pathways, and consequences of the effects on receptors (= ecosystem components) is an essential and integral part of the process (Judd et al., 2015, Piet et al. 2017). The main principles are:

- The effect of a pressure on an ecosystem component results in a potential impact or Impact Risk (IR). IR represents a change in the state expressed as a relative change in equilibrium abundance of the ecosystem component (e.g., species or in the case of habitats the associated biota) compared to an undisturbed situation (Piet et al., submitted). As an impact can only be negative, the proportional change ranges from - 0 (no impact) to +100% IR (maximum impact).
- The cumulative impacts are the sum of all the impacts per ecosystem component and then aggregated into an ecosystem assessment as the average across the components (thus assuming equal importance).

The CIA method proposed for this study is based on the method and database of the EU project Aquacross ([www.aquacross.eu](http://www.aquacross.eu); Borgwardt et al., 2019; and previous work: e.g. Knights et al., 2015). The database of Borgwardt et al. (2019) contains 7771 effect impact chains for the North Sea, which were all semi-quantitatively assessed using (scientific) knowledge from literature supplemented by expert judgement by a large team of international experts. The CIA method has recently been applied to develop a framework for seaweed culture concerning sustainable use of the North Sea (Tonk et al., 2021 ). The output of the CIA is IR expressed as a percentage between 0 and 100%, reflecting the expected pressure-induced loss of a specific ecosystem component relative to an undisturbed situation. A fictive example of the type of results that is produced by the CIA is shown in Figure 4.

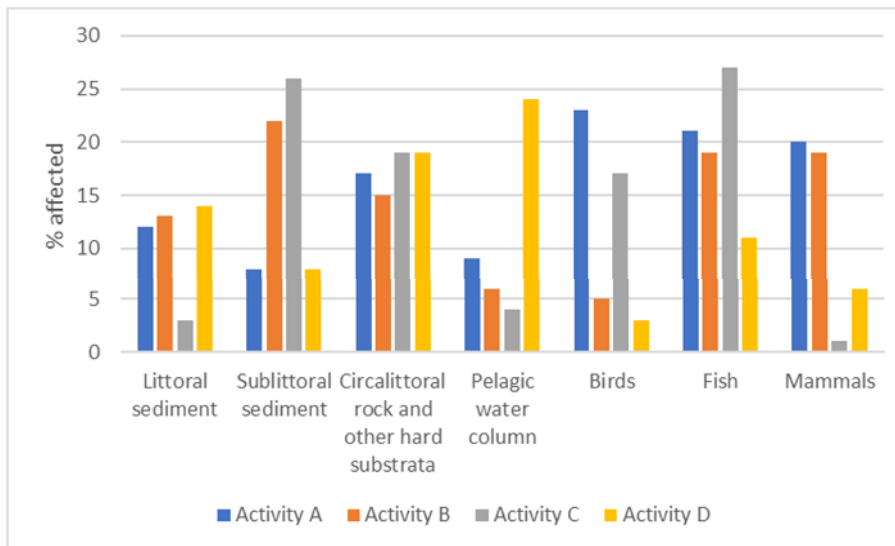


Figure 4. Fictive examples of CIA result.

#### 2.1.1. Approach of the CIA

The output of the CIA:

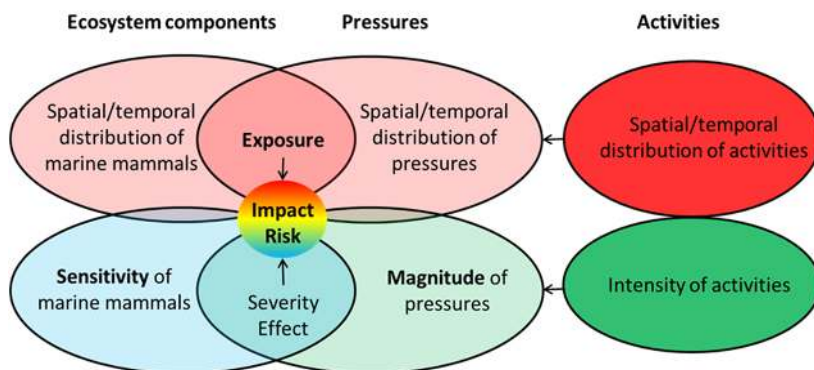
- Is especially informative on relative values, i.e., the differences between the reference situation and the alternative/future situation (baseline scenario and the other scenarios of single-use and multi-use).

- Provides ranking orders of contributors to disturbance.
- Can be used to provide an integrative view of the ecological effects of activities and their pressures on the ecological components of the study area.
- Provides Impact Risk as a measure of potential impact on the biota. This does not reflect the expected actual abundance as can be obtained from monitoring programmes.
- Gives directions for thinking and rough prioritization.

### 2.1.2. Detailed approach

The assessment is based on an exposure-effect approach that estimates Impact Risk (IR, Figure 5) using categories (after Robinson et al., 2013) and assigning numerical scores (adapted from Knights et al. (2015) and Borgwardt et al. (2019)) in combination with quantitative information. The (semi-)quantitative data is applied in a methodological approach based on population dynamics so that the IR represents a change in state expressed as a relative change in equilibrium abundance compared to an undisturbed situation. The Spatial Cumulative Assessment of Impact Risk for Management (SCAIRM) methodology is developed as part of the ICES WGCEAM (Working Group on the use of Cumulative Impact Assessments for Management) and is submitted for publication to Ecological Indicators (Piet et al., submitted).

The linear interaction between a sector/activity, pressure, and ecological component is referred to as an “impact chain” (Knights et al., 2015). For each impact chain, the IR is calculated as the product of exposure and the potential effect and is expressed as the proportional (%) change in equilibrium abundance compared to an undisturbed situation of a particular ecosystem component due to a particular activity-pressure combination. It should be noted that the CIA only assesses first-order impacts. Secondary impacts like i.e., the translation to ecosystem services, need to be performed by an additional methodology. The CIA then aggregates across impact chains to show for example the (1) IR for each ecosystem component resulting from the aggregated activity/activities or (2) the IR caused by each activity or activity-pressure combination to overall biodiversity, i.e., aggregated across ecosystem components.



*Figure 5. The CIA, and its key concept Impact Risk, is based around the principles of environmental risk assessment where risk is based on Exposure and Effect. Exposure is determined by the spatio-temporal overlap between the anthropogenic pressure and the ecosystem component, and the severity of the effect is determined by the magnitude of the pressure and the sensitivity of the ecosystem component.*

In essence the CIA is a risk estimate.  $IR = Exposure * Effect$ , phrased alternatively as  $IR = probability * damage$ . The calculation is composed of several basic concepts in the estimation (Figure 5) (see also Rozemeijer et al., 2021 in UNITED deliverable 4.2 and Rozemeijer et al., 2022):

- **Exposure** is defined as the probability of co-occurrence of the pressure and the ecosystem component and is determined by their spatial and temporal overlap. The exposure score is calculated on the basis of Extent and Dispersal.
- **Spatial extent** is the spatial overlap of each action-pressure combination with an ecosystem component within the area of the activity, e.g. the extra suspended silt in a sand extraction area, e.g. 500m<sup>2</sup>). It was

---

evaluated by considering the spatial distribution of human activities and ecosystem components in the study area, and how much spatial overlap in these there is (Borgwardt et al., 2019). The area of overlap is relative to the area occupied by the ecosystem component in question within the study area. For this study, instead of the extent scores applied by Borgwardt et al. (2019), we used the surface areas of the activities gathered per pilot.

- **Dispersal** refers to the spatial overlap of the pressure when it disperses outside the activity area, e.g., the silt suspension that disperses with the currents (several tenths of km<sup>2</sup>). It evaluates the potential of an activity-pressure impact to spread and increase its spatial overlap with an ecosystem component beyond that of the area of extent where the pressure and ecosystem component overlap initially (Borgwardt et al., 2019).
- The **Effect Potential (EP)** describes the degree to which the ecosystem component is likely to be affected by a pressure (i.e., activity and its pressure) relative to an undisturbed situation. EP can be assumed conceptually identical to sensitivity. The EP consists of a resistance and resilience component. The resistance is interpreted as the proportion of the undisturbed abundance of the receptor that survives the assessment period (usually a single year) in case of exposure to the pressure, where both the stressor and receptor have specific characteristics that determine the sensitivity of that receptor to that stressor. Resistance is based on hazard, i.e., the inherent capacity to cause adverse effects, and magnitude (= the average strength of that pressure in the area co-occurring with the ecosystem component). For both criteria categorical scores are used. The type of response of the ecosystem component to the pressure is categorised as either 'Continuous' or 'Intermittent'. The resistance by continuous interactions is only based on hazard and magnitude, whereas the resistance by intermittent interactions is also determined by the likelihood of interaction and frequency.
- **Hazard** is defined as the relative depletion of the ecosystem component from a single interaction with the pressure at maximum magnitude. Ideally, the consequence of this interaction is quantified through the combination of the magnitude of the pressure and the responsiveness of the ecosystem component to that pressure (e.g., dose-response relationship). Because the information required to quantify hazard is limited, a simplified approach is used by first distinguishing between lethal and sublethal responses and high and low levels.
- **Behaviour** determining the likelihood of interaction addresses the behavioural response of an ecosystem component in case of exposure, thereby avoiding or reducing effect.
- **Frequency** is the frequency of the temporal overlap of each action-pressure combination with an ecosystem component e.g., a migratory bird is only subjected to the pressure collision by a OWF monopile when it passes the region on its migration. Frequency of interactions describes the most likely number of times the activity interacts with an average square kilometre of an ecosystem component in an average year, where they overlap in space (Borgwardt et al., 2019). The frequency of activities was also gathered per pilot.
- **Duration:** is the period of the activity or action as a part of a full year.
- **Magnitude** is the intensity of the pressure for which an appropriate pressure-specific metric will be identified.
- **Persistence** is the length of time that is needed that a pressure disappears after the action stops. I.e., the threat of collision with the monopile disappears immediately where extra silt due to sand extraction can be active for days and weeks. For example, while habitat loss is persistent, organic enrichment is not.
- **Resilience** is the recovery time of the ecological characteristic to return to pre-impact conditions (Knights et al., 2015). Recovery times for species assessments were based on turnover times (e.g., generation times). For predominant habitat assessments, recovery time was the time taken for a habitat to recover its characteristic species of features given prevailing conditions.
- **Recovery times** for species assessments were based on turnover times (e.g., generation times). For predominant habitat assessments, recovery time was the time taken for a habitat to recover its characteristic species of features given prevailing conditions.

### 2.1.3. The calculations

The variables Spatial extent, Dispersal, Frequency, Persistence, Hazard, and Magnitude are estimated in semi-quantitative categories like low to high, incidental to always, etc. Preferably the estimates are derived from literature but in general sufficient research is lacking and the categories per variable were estimated by a panel of experts (formalising their tacit knowledge). These values were translated into numbers and used in formulas to calculate the other variables.

This part only gives the line and development in the calculations. The actual equations can be found in Piet et al. (submitted). The exposure is calculated as a result of the Spatial extent and Dispersal. The Effect Potential is calculated as an intermediate from the Resistance (calculated from Magnitude, Hazard, Behaviour, and Frequency) and Resilience (Recovery times) component. The Impact Risk (IR) is the product of Effect Potential \* Exposure.

For this project, the lacking activities of Solar and Nature restoration were added by evaluations by Ruud Jongbloed, Jacqueline Tamis and Marcel Rozemeijer in a similar approach as Borgwardt et al. (2019). Brigitte Vlaswinkel and Pauline Roos of Oceans of Energy helped with estimating the Solar IRs.

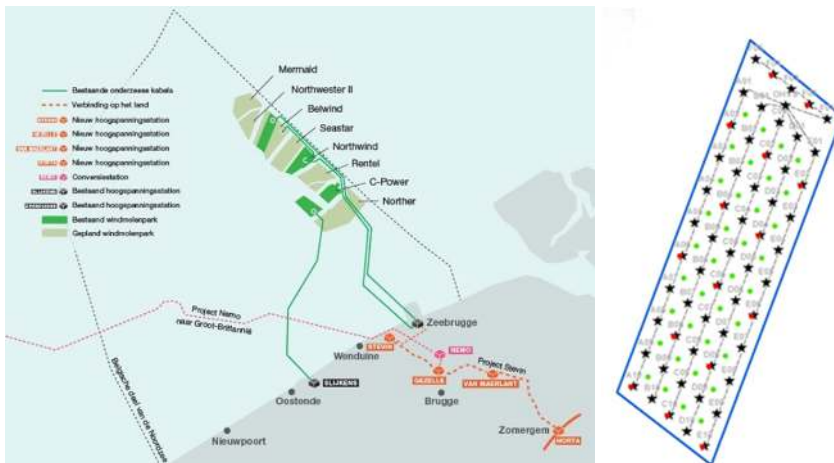


Figure 6. The offshore wind farm of Belwind (operated by Parkwind) serves as the lay-out and set up. Left: It is situated in the Northeast of the Belgium part of the North Sea close to the Dutch border. Right: in-field-electricity cable lay-out (see also Degraer et al., 2011).

### 2.1.4. Upscaling test-size activities to single-use, large-scale activities

A description of the pilots and the activities considered in them can be found in Annex 1. Additionally, for a more detailed description of the ecological situation of the pilots, refer to Deliverable 4.1 of UNITED, “Revision of the current environmental assessment and status of the pilots” (Lukic et al., 2020).

In UNITED, three pilots are at experimental stages: the German, Dutch and Belgian pilots, while the Danish and Greek pilots are already running at a commercial level, so they were calculated in the characteristics they have. For the three experimental pilots, scenarios were designed in which hypothetical large-scale activities occur. Using these scenarios also gave the opportunity to develop a common approach across pilots, which makes for an easier comparison between pilots.

The same scenario was used for the Belgian, German, and Dutch pilots across all work packages, and was defined with the following steps:

- **Standardised OWF:** the Belgium OWF Belwind (Figure 6) was chosen as the standard OWF. One adaption was made by having the electricity transformer platform placed outside the OWF in order to simplify calculations. Belwind was chosen because it is an existing OWF within one of the pilots which allows multi-use. Risk evaluations, negotiations on risk measures and mitigations have been performed and settled based on this context. Multi-use is actually happening. An EIA for the OWF had been made previously and monitoring data were already available (Di Marcantonio et al., 2007).

- A disadvantage is that Belwind is an older OWF with smaller wind turbines and less distance between them. In Belwind the distances between monopiles are 700 m more or less parallel to the coast and 500 m perpendicular to the coast, whereas a newer OWF like Borssele II on the Dutch side has monopiles separated by 1000 meters each side. The latter has more space available for multi-use activities, hence more recent (and hence relevant) calculations. However, since the aim of the project is to show proof of concept rather than actual evaluations, this argument is less valid than the other arguments above.
- **Location:**
  - For the Belgian case, the actual location of Belwind was chosen.
  - For the German case, the location of OWF DanTysk was chosen because it is directly adjacent (less than one nautical mile away) to the FINO3 platform (Forschungsplattform in Nord- und Ostsee Nr. 3), the pilot location.
  - For the Dutch pilot, the location of Prinses Amalia Wind Park (PAWP) was selected (formerly known as Q7 WF). It is an existing OWF for which an EIA has been previously made and for which monitoring data is available. In addition, around PAWP a new OWF (Hollandse Kust Noord, lot V) will be constructed, for which also monitoring data and an EIA are available.
  - For the aspect “distance to the shore” PAWP represents a nearby OWF, DanTysk represents a far OWF and Belwind midway (relative to each other, Table 1).
- **Surface:** for the CIA methodology a surface estimate is needed for all activities. In the methodology this is used to calculate the “extent of overlap” (Note that; the difference between single-use and multi-use lay in both the extent and the duration/frequencies of actions and thereby pressures).
  - The Belwind model OWF, which was taken as the basis for OWFs in this study (representative for all pilots), has an area of 17 km<sup>2</sup> (Figure 6).
  - To calculate the available space for activities, two safety zones were used:
    - When not anchoring, 100 m around the monopile and 100 m at either side of the infield cable.
    - When anchoring: 150 m around the monopile and 100 m at either side of the infield cable.
    - To the stretches between the monopiles more or less perpendicular to the coast lacking infield cables, no safety zone was assigned. This provides the opportunity to enable better manoeuvring for all users.
  - The scour protection layer<sup>2</sup> was calculated using a radius of 20 m including the monopile (5 m). For nature restoration, a quarter of the surface was subtracted being part of the safety zone of the infield cable.
  - An ecological reference surface around the pilot had to be defined to accommodate the dispersal of the pressures. The total reference (i.e. study) area (pilot and adjacent dispersal zone) was set to 22 km<sup>2</sup> for each of the countries/pilots.
  - All calculated surfaces are given in Table 2.
  - For the calculations several approaches were used (Table 2, Table 3):
    - Belgium, Germany, Netherlands: activities scaled to each 50% of the pilot.
    - For seaweed and shellfish culturing it was assumed to have only one line (two points anchoring). This is the actual Belgium situation where due to risk consideration no more lines are allowed (DeClerq, Kerkhove, Pers. Comm.). The risks perceived by operators were e.g. mobilisation of the lines, entangling with the turbines, anchors damaging infield cables, maintenance vessels entangling with lines.
    - For solar it was assumed to occupy the complete area between the turbines (a cell) that remains after subtraction of the safety zones in solar panels.

<sup>2</sup> The scour protection prevents erosion of sand around wind turbines and other objects through layers of rocks. The scour protection includes a preinstalled filter layer of small-sized rocks (e.g. 5 cm in diameter) covered by an armour layer of larger rocks (e.g. 40 cm in diameter).

*Table 1. Data on the cable length (in kms) of the different offshore wind farms used for their location. The total length of the infield cables was summed where the information was available (infield cable lengths summed:  $\Sigma$ infield cable). The  $\Sigma$ infield cable of Belwind was used for further impact assessment. At Middelgrunden, two cables were installed at a distance of 15 m (summed in the table).*

OWF used for location	$\Sigma$ infield cable	export cable	land cable
DanTysk	108	160	45
PAWP		23	4.4
Belwind	48	52	3
Middelgrunden	3.4	(2*3.5=) 7	1.5

*Table 2. calculated surfaces (in m<sup>2</sup>) available for activities using the surface of the Belwind OWF and the rules as explained in section 2.1.4. The available surfaces are given for anchoring multi-use activities and when not anchoring.*

Type of use (OWF or multi-use activity)	Anchoring		Not Anchoring	
	m <sup>2</sup>	%	m <sup>2</sup>	%
Total surface available for activities	17000000	100	17000000	100
Area remaining to the OWF	8625830	51	5922467	35
Area available when one additional activity	8374170	49	11077533	65
Area available when two activities (50% each)	4187085	25	5538767	33
Scour protection area for nature restoration	49480	0.3	49480	0.3

*Table 3. Activities proposed for the different pilots (BE: Belgium; DE: Germany; DK Denmark; NL: Netherlands; GR: Greece) and related areas (km<sup>2</sup>) as included in the CIA. Areas are shown for single-use/multi-use application. The area in Multi Use application reflects the required area in addition to the area already required for the main or first activity (area of main activity is indicated in bold), assuming maximum area reduction.*

United Activity	BE	DE	DK	NL	GR
Renewable energy					
Wind farms	17 / 17	17 / 17	0.35 / 0.35	17 / 17	
Export cables	1 / 1	3.2 / 3.2	0.12 / 0.12	0.5 / 0.5	
Solar platforms				4.2 / 0	
Aquaculture					
Macro-algae	4.2 / 0	4.2 / 0		4.2 / 0	
Shellfish	4.2 / 0	4.2 / 0			
Fin-fish					0.07 / 0.07
Nature development					
Oyster reefs	0.049 / 0				
Tourism					
Diving			4 / 3.22		1.30 / 1.23
Day trips			0.0175 / 0		
Touristic fishing			0.78 / 0.43		

### 2.1.5. Baseline scenario

To assess the consequences of the design of the various pilots a baseline CIA (reference situation or generic baseline scenario) is calculated using the SCAIRM methodology, (Piet et al., submitted). This represents the activities at average intensities on a North Sea scale. The OWFs and activities are assumed to be placed at locations where only fishery, shipping and recreational activities were taking place. Therefore, only these activities are considered and not others as e.g. Oil & Gas. For the baseline, a set of common activities on the North Sea is selected:

- Touristic fishing (angling)
- Benthic trawls and dredges
- Boating/Yachting (with engine)
- Boating/Yachting/Watersports (without engine)
- Nets (fixed/set/gillnets/other nets/lines)
- Pelagic trawls
- Shipping

### 2.1.6. Comparison of singles uses and multi-use in the pilots

The activities included within the pilots (Table 3) are assessed for Single Use and Multi-Use Approach, hereafter referred to as SU and MU, respectively. For SU each activity is assessed separately (i.e., without consideration of other activities) and the total IR per pilot is estimated by summation of the Impact Risk of each activity. For MU, it is assumed that activities are combined and thereby may reduce their cumulative Impact Risk. The combination may involve sharing space (reflected in the area extent) or time (reflected in duration and/or frequency) of specific combinations of activities.

#### Actions

For the purposes of this assessment, the SCAIRM methodology activities are further elaborated into actions, e.g., on the installation of foundations, manual labour etc. See Annex 2 for detailed descriptions. This approach is intended to increase the resolution for the sharing of actions like e.g., shipping.

#### Variables for the SU and MU calculations: extent and duration

The areas available for multi-use are estimated by taking the area of the OWF minus the area of the safety zone around the OWF installations (turbines and infield cables).

As mentioned above, the combination of activities in MU may involve sharing space which is expressed by a reduction in extent for MU compared to SU. The potential reduction in extent is presented in Table 3 showing the area required for SU/MU. OWFs are taken as the key activity, for which the extent cannot be reduced. Other activities may be combined with wind farms and will be situated within the OWF area, as additional activities. As such it does not require additional space, and their extent is maximally reduced to zero. However, this reduction may not apply to all actions required for the activity, as some actions are exclusive for a specific activity or are not expected to be shared (Table 4). For example, aerial structures are only used by OWF therefore sharing (hence extent reduction) is not applicable. Another example is foundations and installations, an action used by multiple activities but not expected to be shared.

The differences between SU and MU design are also identified via the duration of the actions (time required per action) per activity (Table 5). For example, activities in MU can share shipping time, thereby reducing costs and disturbances. Data input was provided by the United partners responsible for each pilot (Annex 3).

*Table 4. Identification of sharing space (area extent) in MU (Multi Use), by indicating actions expected to co-exist within the pilots and therewith reduce in extent in MU.*

Action (and Phase)	Change of extent in MU	BE	DE	DK	NL	GR
<i>Installation</i>						
Aerial structures - alterations	Not applicable	N	N	N	N	N
Benthic hard substrates - alterations	No sharing	N	N	N	N	N

Action (and Phase)	Change of extent in MU	BE	DE	DK	NL	GR
Dredging and disposal	Not applicable	N	N	N	N	N
Electric and telecommunication cables in the seafloor - alterations	Yes, extent reduction is relevant for NL pilot (OWF and solar energy combined use of cables)	N	N	N	Y	N
Electric and telecommunication cables in the water column - alterations	Not applicable	N	N	N	N	N
Floating structures - alterations	No sharing	N	N	N	N	N
Foundation and installations	No sharing	N	N	N	N	N
Lines or nets in the water column - alterations	Not applicable	N	N	N	N	N
Manual labor	Yes, extent reduction is relevant for BE, DE and NL pilot (OWF and additional activities both use manual labor)	Y	Y	N	Y	N
Pelagic structures - alterations	No sharing	N	N	N	N	N
Pre-installation actions	No sharing	N	N	N	N	N
Shipping	Yes, extent reduction is relevant for all pilots	Y	Y	Y	Y	Y
Species culturing - set up	Not applicable	N	N	N	N	N
<b>Operational</b>						
Accommodation of people	Yes, extent reduction is relevant for BE, DE and NL pilot (OWF and additional activities both use accommodation)	Y	Y	N	Y	N
Aerial structures - operation	Not applicable	N	N	N	N	N
Benthic hard substrates - presence	No sharing	N	N	N	N	N
Benthic hard substrates - alterations	No sharing	N	N	N	N	N
Diving	Yes, extent reduction is relevant for all pilots	Y	Y	Y	Y	Y
Electric and telecommunication cables in the seafloor - presence	Yes, extent reduction is relevant for NL pilot (OWF and solar energy combined use of cables)	N	N	N	Y	N
Aerial structures - maintenance	Not applicable	N	N	N	N	N
Electric and telecommunication cables in the seafloor - alterations	Yes, extent reduction is relevant for NL pilot (OWF and solar energy combined use of cables)	N	N	N	Y	N
Electric and telecommunication cables in the water column - alterations	Not applicable	N	N	N	N	N
Floating structures - presence	Not applicable	N	N	N	N	N
Floating structures - alterations	Not applicable	N	N	N	N	N
Fouling removal	No sharing	N	N	N	N	N
Hard substrates in the water column	No sharing	N	N	N	N	N
System operation	Yes, extent reduction is relevant for NL pilot (OWF and solar energy combined use of system)	N	N	N	Y	N
Lines or nets in the water column - presence	Not applicable	N	N	N	N	N
Lines or nets in the water column - alterations	Not applicable	N	N	N	N	N
Manual labor	Yes, extent reduction is relevant for BE, DE, DK and NL pilot (OWF and additional activities both use manual labor)	Y	Y	Y	Y	N
Monitoring of the environment	Yes, extent reduction is relevant for BE, DE and NL pilot (OWF and additional activities both include this action)	Y	Y	N	Y	N
Monitoring of the targets	Yes, extent reduction is relevant for BE, DE and NL pilots (OWF and additional activities both include this action)	Y	Y	N	Y	N
Pelagic structures - presence	No sharing	N	N	N	N	N

Action (and Phase)	Change of extent in MU	BE	DE	DK	NL	GR
Shipping	Yes, extent reduction is relevant for all pilots	Y	Y	Y	Y	Y
Species culturing - growing	Not applicable	N	N	N	N	N
<b>Decommissioning</b>						
Aerial structures - alterations	Not applicable	N	N	N	N	N
Benthic hard substrates - alterations	No sharing	N	N	N	N	N
Electric and telecommunication cables in the seafloor - alterations	Yes, extent reduction is relevant for NL pilot (OWF and solar energy combined use of cables). However, cables do not need to be removed (tolerance situation in the Netherlands)	N	N	N	Y	N
Floating structures - alterations	Not applicable	N	N	N	N	N
<p><b>Not applicable:</b> the action is only included for the key activity or for an additional activity, but not for both.</p> <p><b>No sharing:</b> Structures/installations will not be shared, therefore no reduction in extent for MU (Multi Use) for this action.</p> <p>Columns on the right indicate for each pilot (<b>BE:</b> Belgium; <b>DE:</b> Germany; <b>DK:</b> Denmark; <b>NL:</b> the Netherlands; <b>GR:</b> Greece) whether the extent is reduced in MU (<b>N:</b> no extent reduction, the SU extent applies; <b>Y:</b> extent reduction, the MU extent applies). See Table 3 for the SU and MU extent values.</p>						

**Table 5. Identification of sharing time (duration) in MU (Multi Use), based on the expected duration per action in SU (Single Use) and MU as provided by the project partners (BE: Belgium; DE: Germany; DK: Denmark; NL: the Netherlands; GR: Greece). It is only indicated whether the duration is reduced in MU (No: no duration reduction, the SU duration applies; Yes: duration reduction, the MU duration applies). The duration values are provided in Annex 3.**

Action	BE	DE	DK	NL	GR
<b>Installation</b>					
Aerial structures - alterations	No	No	No	No	No
Benthic hard substrates - alterations	Yes	Yes	No	Yes	No
Dredging and disposal	Yes	No	No	No	No
Electric and telecommunication cables in the seafloor - alterations	No	No	No	Yes	No
Electric and telecommunication cables in the water column - alterations	No	No	No	No	No
Floating structures - alterations	Yes	Yes	No	Yes	No
Foundation and installations	No	No	No	No	No
Lines or nets in the water column - alterations	Yes	Yes	No	Yes	No
Manual labour	No	No	No	No	No
Pelagic structures - alterations	No	No	No	No	No
Pre-installation actions	Yes	Yes	No	Yes	No
Shipping	No	No	Yes	No	No
Species culturing - set up	No	No	No	No	No
<b>Operation</b>					
Accommodation of people	No	No	No	No	No
Aerial structures - operation	No	No	No	No	No
Benthic hard substrates - presence	Yes	No	No	No	No
Benthic hard substrates - alterations	No	No	No	No	No
Diving	Yes	No	No	Yes	Yes
Electric and telecommunication cables in the seafloor - presence	No	No	No	Yes	No
Aerial structures - maintenance	No	No	No	No	No
Electric and telecommunication cables in the seafloor - alterations	No	No	No	No	No
Electric and telecommunication cables in the water column - alterations	No	No	No	No	No

Action	BE	DE	DK	NL	GR
Floating structures - presence	No	No	No	Yes	No
Floating structures - alterations	No	No	No	Yes	No
Fouling removal	No	No	No	No	No
Hard substrates in the water column	No	No	No	No	No
System operation	No	No	No	No	No
Lines or nets in the water column - presence	No	No	No	No	No
Lines or nets in the water column - alterations	No	No	No	No	No
Manual labour	No	No	No	No	No
Monitoring of the environment	Yes	Yes	No	Yes	No
Monitoring of the targets	No	No	No	No	No
Pelagic structures - presence	No	No	No	No	No
Shipping	No	No	No	No	Yes
Species culturing - growing	No	No	No	No	No
<b>Decommissioning</b>					
Aerial structures - alterations	No	No	No	No	No
Benthic hard substrates - alterations	Yes	Yes	No	Yes	No
Electric and telecommunication cables in the seafloor - alterations	No	No	No	No	No
Floating structures - alterations	No	No	No	Yes	No
Fouling removal	No	No	No	No	No
Foundation and installations	No	No	No	No	No
Lines or nets in the water column - alterations	Yes	Yes	No	Yes	No
Manual labour	No	No	No	No	No
Pelagic structures - alterations	No	No	No	No	No
Seabed restoration	No	No	No	No	No
Shipping	No	No	No	No	No

### 2.1.7. Nature enhancement

Potential benefits for nature by the pilot activities are assessed as the contribution to abundance of hard substrate benthos, relative to the abundance at the start of the activities. As such, these benefits are in line with IR (expressed as a relative change in equilibrium abundance compared to an un-disturbed situation) and can be used as counterbalance to IR resulting in an overall change in state of an ecosystem component.

The contribution is calculated as the average change in abundance per year over a 10-year period (which is an arbitrary choice) assuming logistic growth at growth rates that match the recovery times used for assessment of IR. The resulting contribution to abundance is multiplied by the added surface of hard substrate habitats in order to assess the enhancement of hard substrate habitats. These are then combined with the reductions of hard substrate habitats (through IRs) to estimate the potential net change in hard substrate biota.

## 2.2. Results of the CIA

### 2.2.1. Baseline scenario

The **baseline assessment** showing the cumulative impacts from a set of common activities **on the North Sea** expressed as IR, **shows that fish suffer the biggest threat followed by benthic habitats** (Figure 7, left). Benthic fisheries contribute most to the IR, followed by set nets and pelagic fisheries. Baseline IR exceeds IR from pilot activities

operated in SU (Figure 7, right). Therefore, it can be expected that for all ecosystem components, except birds, the total IR in the operational phase of the pilot area will be reduced compared to the situation prior to the pilot development (i.e., baseline situation). **In the case of SU activities, birds suffer the biggest threat.** Wind farms contribute most to the IR, followed by finfish culture.

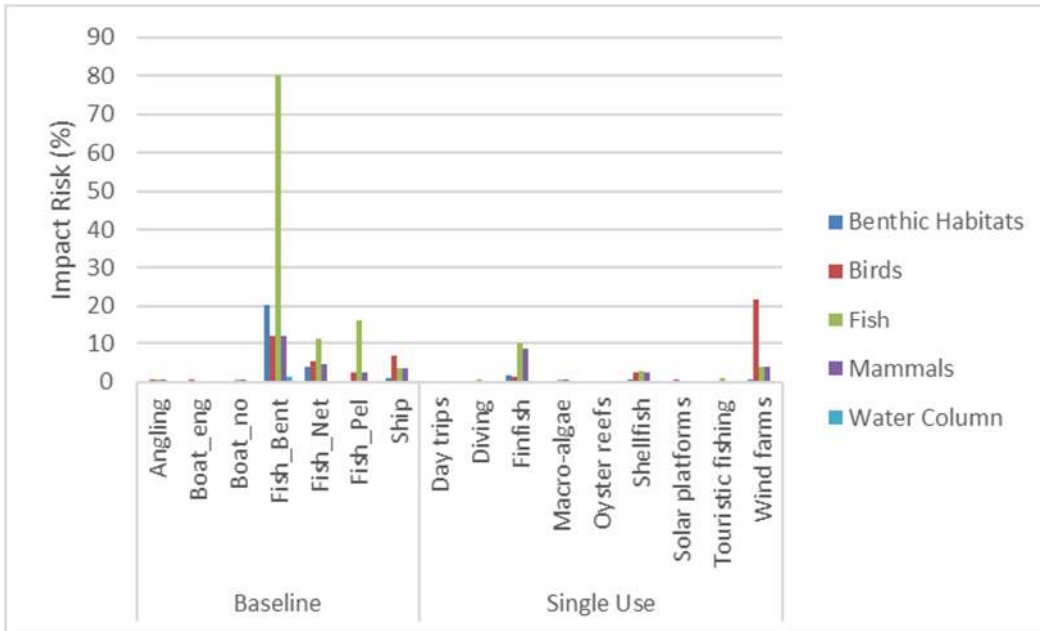


Figure 7. Impact Risk from activities on ecosystem components in the Baseline (North Sea average, left) and SU pilots (right). Activities included in this baseline are: Angling; Boat\_eng (Boating / Yachting, with engine); Boat\_no (Boating / Yachting / Water sports, without engine); Fish\_Bent (Benthic trawls and dredges); Fish\_Net (Nets, fixed/set/gillnets/other nets/lines); Fish\_Pel (Pelagic trawls); Ship (Shipping).

### 2.2.2. Predicted impact per pilot

The IR on Ecosystem Components (ECs) from activities in SU and MU is shown for each pilot in the installation, production, and decommissioning phase (Figure 8). It reveals that the highest IR is expected for the production phase. In many cases, the IR in MU is lower than the IR in SU. The IR in MU is never higher than the IR in SU. Differences between IR of SU and IR of MU are most pronounced for the Dutch and Belgian pilots.

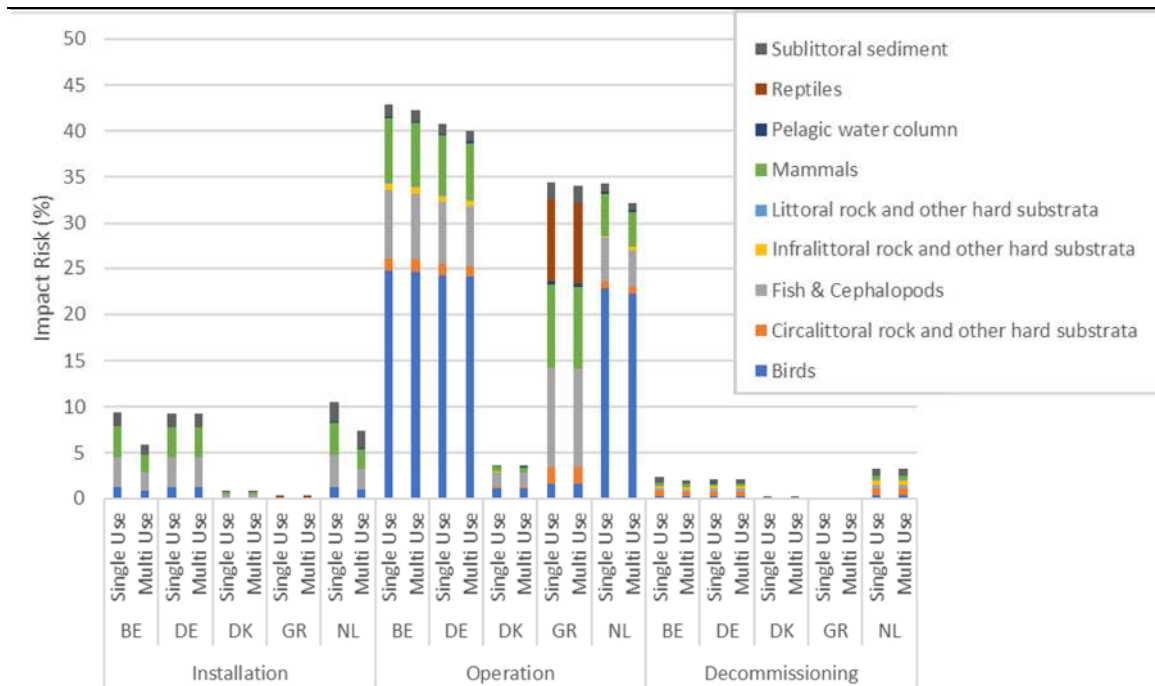


Figure 8. Impact Risk on ecosystem components in the Belgian (BE), German (DE), Danish (DK), Greek (GR) and Dutch (NL) pilot by activities in SU and MU for the Installation phase (left), Operation phase (middle) and Decommissioning phase (right).

To show more detail for each pilot, the IR on ECs from the installation, operation, and decommissioning activities in SU and MU is shown in Sankey diagrams (Figure 9 to Figure 13).

Sankey diagrams are used to illustrate the flow of IRs from activity to action to pressure to ECs. The ECs are positioned at the centre of the Sankey. The SU activities are positioned at the left of the ECs, with IR flowing from left to right. The MU activities are positioned at the right of the ecosystem components, with IR flowing from right to left. Differences in IR between MU and SU are indicated by colouring: orange for relatively large differences and light blue for relatively small differences. Blue flows indicate no difference in IR between SU and MU.

The results are briefly described below, first as a general overview and then per pilot and phase, thereby focusing on the main impact on ECs from SU and MU activities.

#### General overview of IRs

- Installation:** In the installation phase for all pilots (except Greece) most IR is caused by impulsive noise from pre-installation actions on fish and mammals. The water column is the least impacted. Although relatively (large) differences in IR from MU compared to SU are shown, on an absolute scale the reduction is only noticeable for the Belgium and Dutch pilot. In Greece, the highest threat comes from the introduction of (non-) synthetic compounds from species culturing (potential release of compounds from use of biocides, pesticides, medicines and antifouling during set up) instead of impulsive noise. Note that there are no differences in MU compared to SU applied in the Greek pilot.
- Operation:** During operations for the Belgian, German, and Dutch pilots, birds are the most threatened compared to other ecosystem components. The highest IR is caused by death or injury by collision (arial structures, i.e., turbine rotors). In the Danish pilot, fish are the most threatened by the extraction of flora and fauna, closely followed by birds threatened by collision. In Greece, fish, mammals, and reptiles are impacted most, with the highest IR caused by the introduction of (non) synthetic compounds (potential release of compounds from the use of biocides, pesticides, medicines and antifouling) from species culturing. Other threats are related to discharges of particulate waste from lost feed and faeces (changes in input

---

of organic matter, N&P enrichment and smothering). Although there are differences in IR from MU compared to SU, the absolute reduction in IR is very minor.

- **Decommissioning:** most IR is caused for benthic habitats by total habitat loss and abrasion/damage. Differences in IR between SU and MU are very low to none.

#### IR per pilot

##### Pilot Belgium (Figure 9)

- **Installation:** Most IR is caused by impulsive noise from pre-installation actions on fish and mammals, both in SU and MU. The orange-colored flows of these impact chains indicate relatively large differences between IR in MU compared to SU; in MU the IR is greatly reduced compared to SU. Benthic habitat (sublittoral sediment) is mostly impacted by abrasion/damage caused by several actions, which is lower in MU (light blue colored flows). Birds are mostly threatened by disturbance from several actions, which is also noticeably lower in MU.
- **Operation:** During operations, birds are most threatened compared to other ecosystem components. Highest IR is caused by death or injury by collision (aerial structures, i.e. turbine rotors). Although there are differences in IR from MU compared to SU, as indicated by the orange (relatively large difference) and light blue (relatively small difference) flows, this is hardly noticeable in this figure. This means the absolute reduction in IR is very small.
- **Decommissioning:** Most IR is caused for benthic habitats by total habitat loss from decommissioning, which is very similar for both SU and MU. Abrasion/damage also causes a relatively high IR, especially in SU. This is indicated by the orange flow (relatively large difference).

##### Pilot Germany (Figure 10)

- **Installation:** Most IR is caused by impulsive noise from pre-installation actions on fish and mammals. Birds and sublittoral sediment are moderately impacted by mostly disturbance and abrasion/damage, respectively. The water column is the least impacted. Although the orange and light blue flows indicate relatively high and low changes (respectively), these are hardly noticeable in absolute IR from MU compared to SU.
- **Operation:** During operations, the most threatened EC are birds, with the highest IR caused by death or injury by collision (aerial structures, i.e., turbine rotors). Habitats are the least affected. There are no noticeable changes in absolute IR caused by MU compared to SU.
- **Decommissioning:** Most IR is caused for benthic habitats by total habitat loss from decommissioning, which is very similar for both SU and MU. Abrasion/damage also causes a relatively high IR, especially in SU.

##### Pilot Denmark (Figure 11)

- **Installation:** Most IR is caused by impulsive noise from foundations and installations on fish and mammals. The water column is the least impacted. There are no noticeable differences in IR from MU compared to SU.
- **Operation:** During operations, the most threatened EC are fish and birds, with the highest IR caused by the extraction of flora and fauna (touristic fishing) and death or injury by collision (turbine rotors), respectively. Habitats are the least affected. There are no noticeable changes in IR caused by MU compared to SU.
- **Decommissioning:** The EC most impacted during decommissioning is infralittoral rock and other hard substrate, although (except for the water column), all ECs are considerably impacted. The highest IR is caused by habitat loss. The estimated IR from MU is identical to the IR from SU.

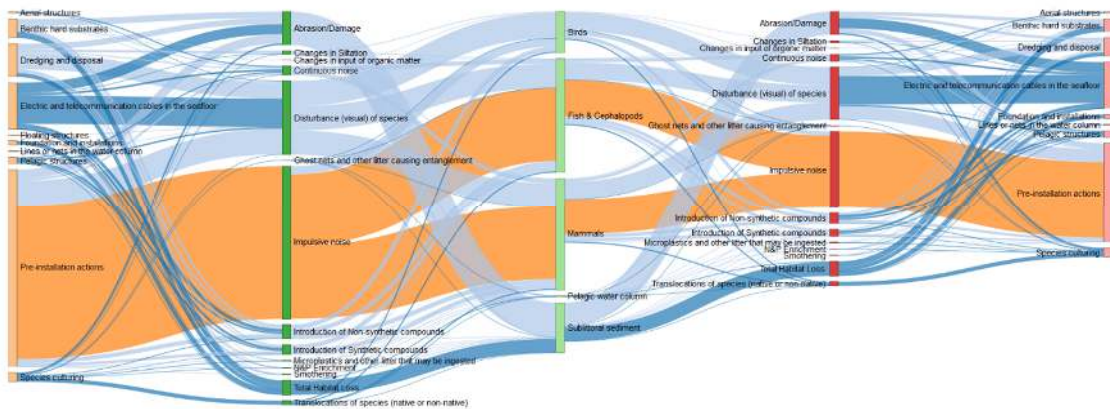
##### Pilot The Netherlands (Figure 12)

- **Installation:** During installation, the most threatened ECs are fish and mammals, with the highest IR caused by impulsive noise from pre-installation actions. Note that in MU, the pre-installation action causes much less IR compared to SU and subsequently the IR for fish and mammals is lower in MU than the IR in SU.

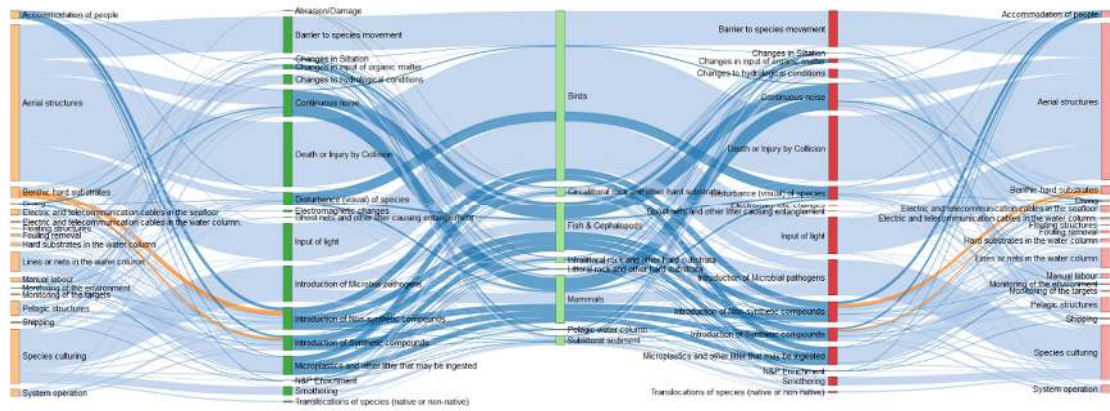
- 
- **Operation:** During operations, the most threatened EC are birds, with the highest IR caused by death or injury by collision (arial structures, i.e., turbine rotors). Habitats are the least affected. The colored flows indicate a change in IR from MU compared to SU. This can be observed for birds, fish, and mammals, where the IR in MU is slightly lower than in SU.
  - **Decommissioning:** Most IR is caused for benthic habitats by total habitat loss from decommissioning, which is very similar for both SU and MU. Abrasion/damage also causes a relatively high IR for benthic habitats. Species are mainly impacted by disturbance. The colored flows indicate change in IR from MU compared to SU. This is however hardly noticeable in the IR for ECs.

#### Pilot Greece (Figure 13)

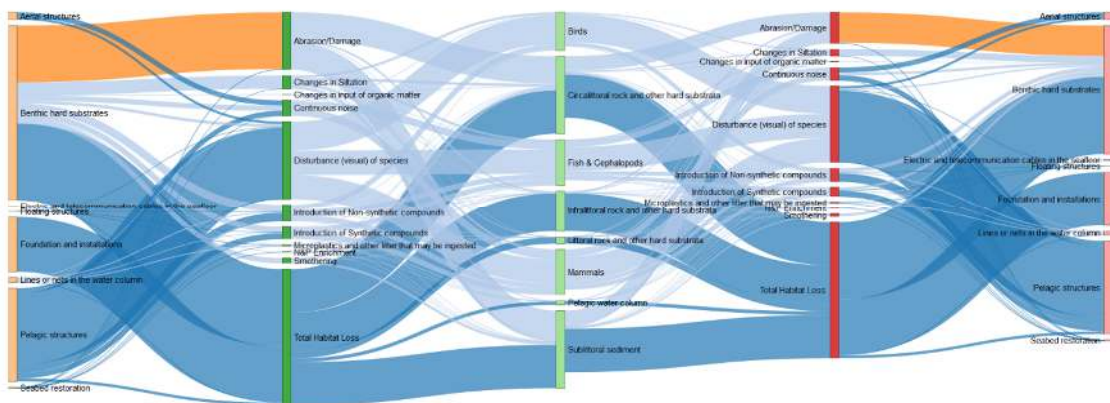
- **Installation:** During installation, all species groups are mostly threatened compared to habitats, with highest IR caused by the introduction of (non-) synthetic compounds (potential release of compounds from the use of biocides, pesticides, medicines and antifouling) from species culturing. Note that there are no differences in MU compared to SU.
- **Operation:** The ECs mostly threatened are fish, mammals and reptiles compared to habitats, with highest IR caused by the introduction of (non-) synthetic compounds (potential release of compounds from the use of biocides, pesticides, medicines and antifouling) from species culturing.
- **Decommissioning:** During decommissioning, all ECs are threatened, although the water column very minor. Note that there are no differences in MU compared to SU.



A. Installation BE

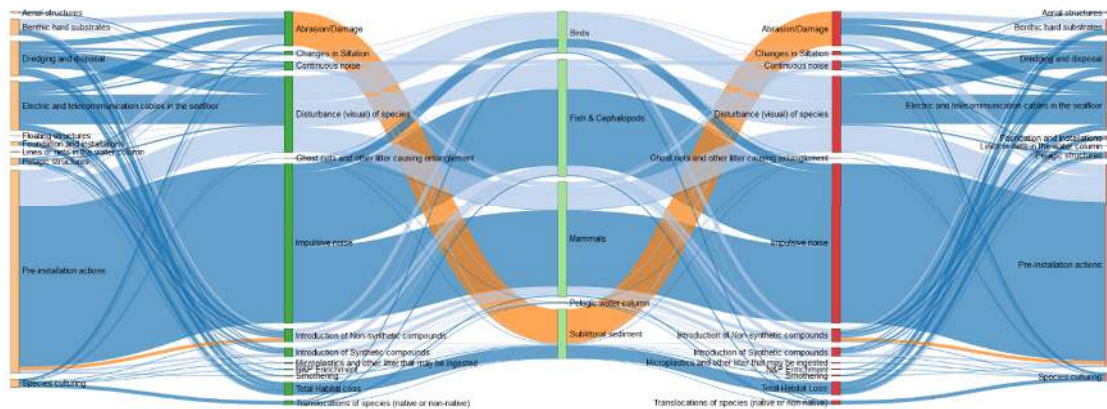


B. Operation BE

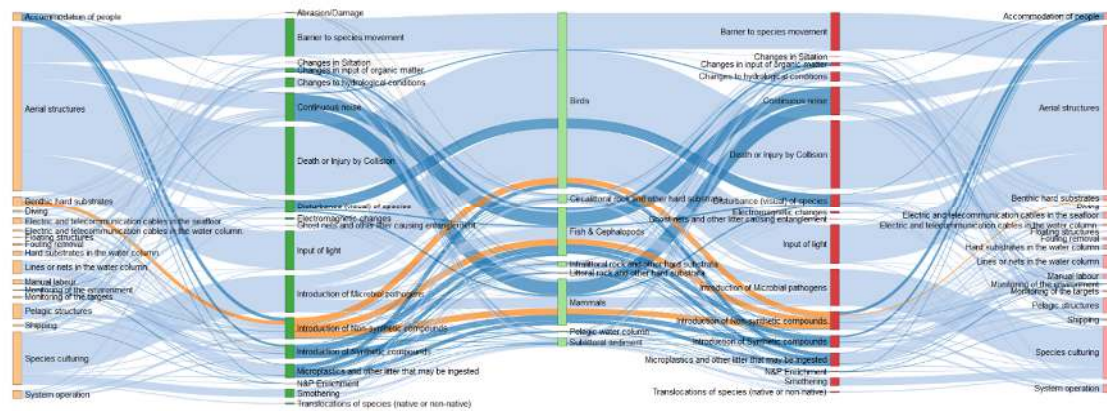


C. Decommissioning BE

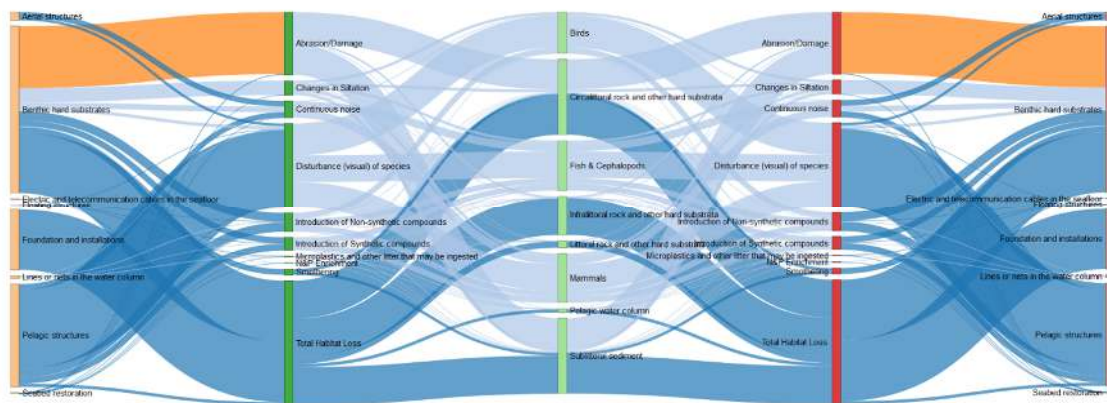
Figure 9. Sankey diagram showing the flow of Impact Risk on ecosystem components in the Belgian pilot for the Installation phase (top), Production phase (middle) and Decommissioning phase (bottom). The ecosystem components are shown in the middle of the Sankey, with the SU activities at the left (IR flowing from left to right) and the MU activities at the right (IR flowing from right to left). Colors indicate the differences between IR from SU and MU: orange = relatively large differences; light blue = relatively small differences; blue = no difference in IR between SU and MU.



A. Installation DE

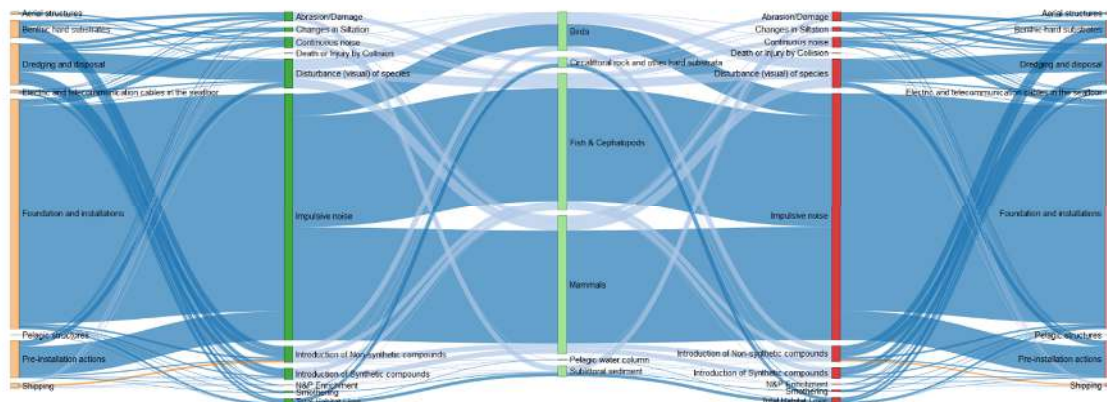


B. Operation DE

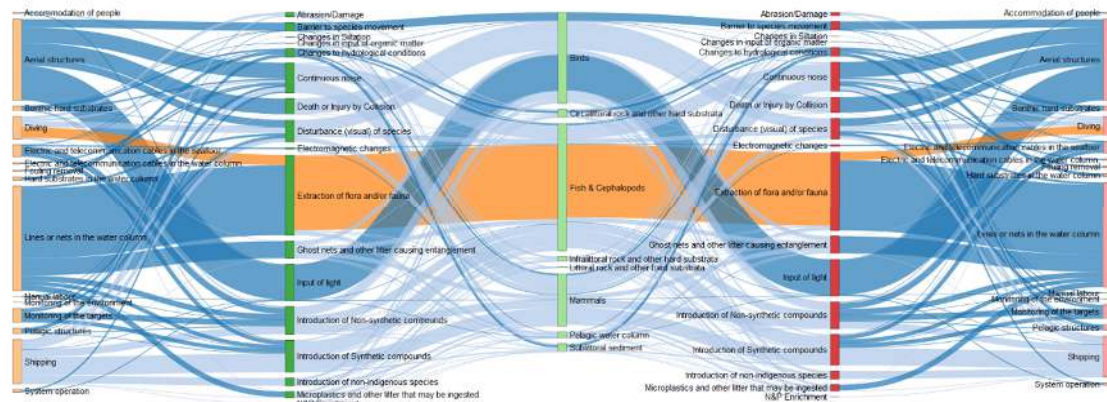


C. Decommissioning DE

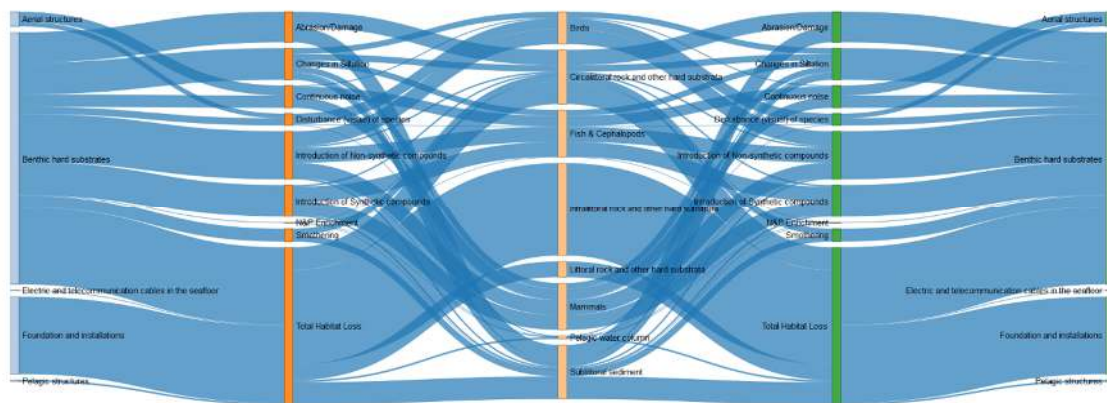
Figure 10. Sankey diagram showing the flow of Impact Risk on ecosystem components in the German pilot for the Installation phase (top), Production phase (middle) and Decommissioning phase (bottom). The ecosystem components are shown in the middle of the Sankey, with the SU activities at the left (IR flowing from left to right) and the MU activities at the right (IR flowing from right to left). Colors indicate the differences between IR from SU and MU: orange = relatively large differences; light blue = relatively small differences; blue = no difference in IR between SU and MU.



A. Installation DK

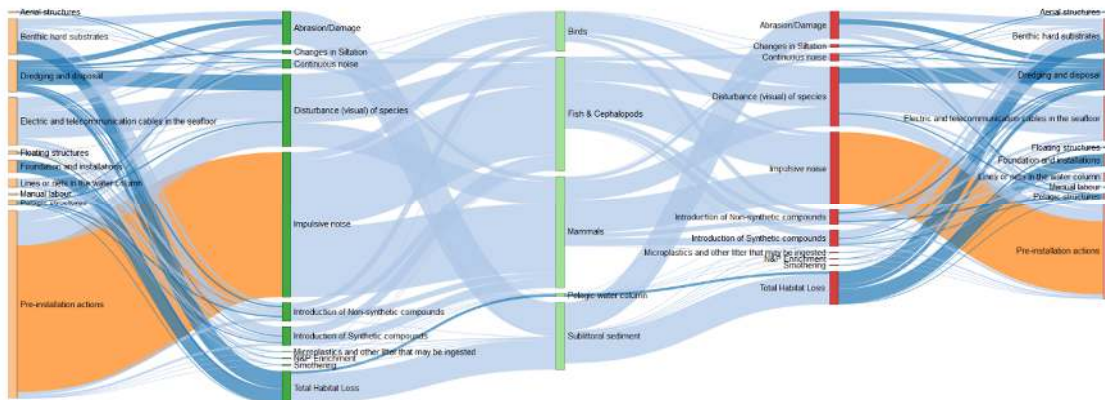


B. Operation DK

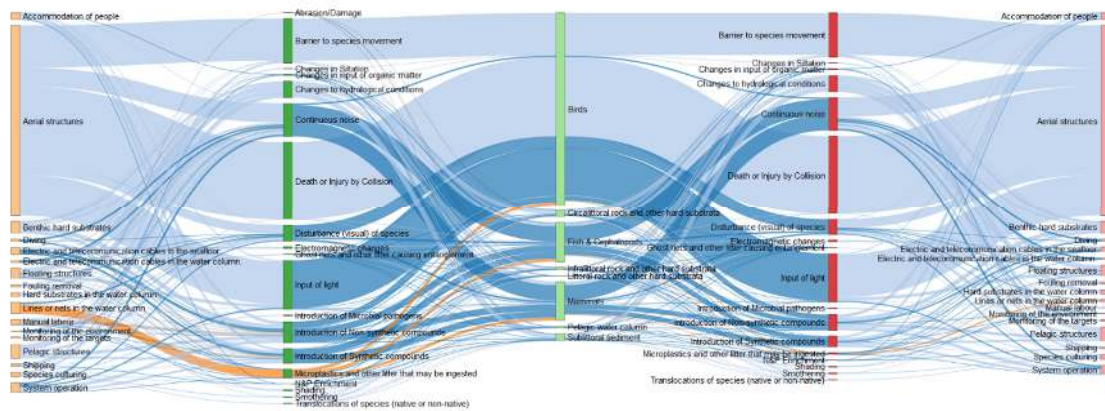


C. Decommissioning DK

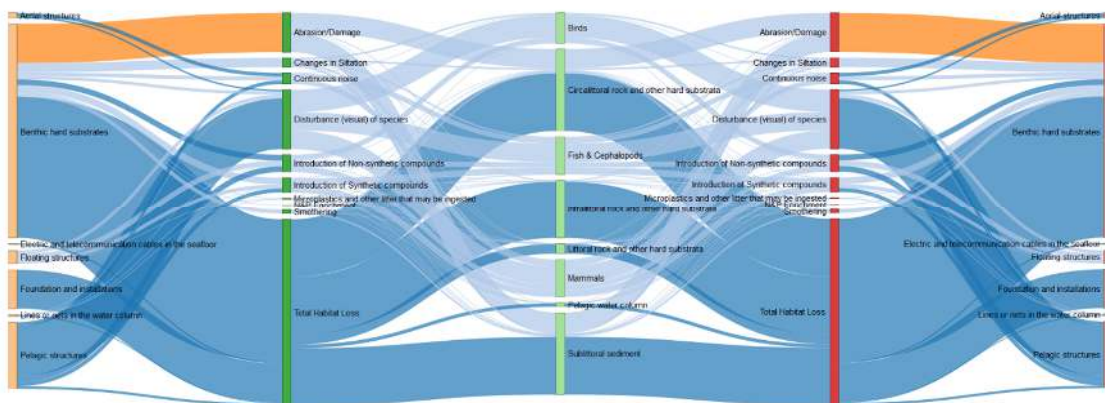
Figure 11. Sankey diagram showing the flow of Impact Risk on ecosystem components in the Danish pilot for the Installation phase (top), Production phase (middle) and Decommissioning phase (bottom). The ecosystem components are shown in the middle of the Sankey, with the SU activities at the left (IR flowing from left to right) and the MU activities at the right (IR flowing from right to left). Colors indicate the differences between IR from SU and MU: orange = relatively large differences; light blue = relatively small differences; blue = no difference in IR between SU and MU.



A. Installation NL

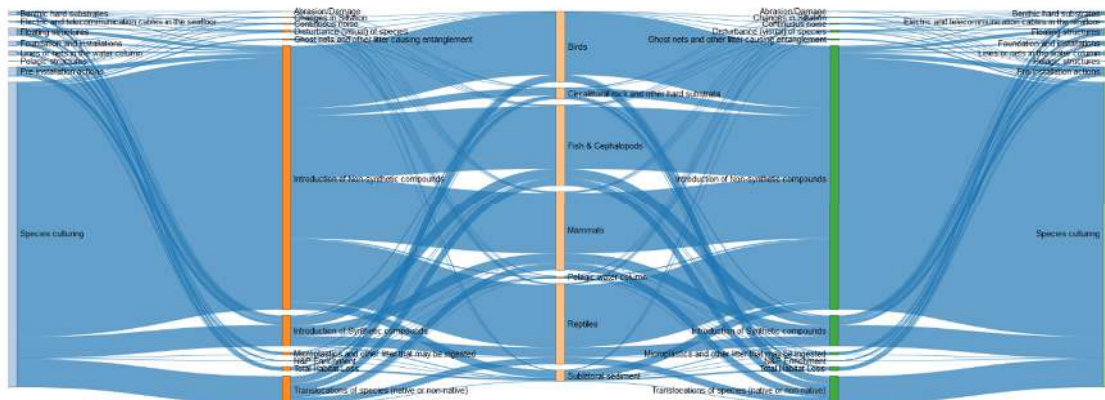


B. Operation NL

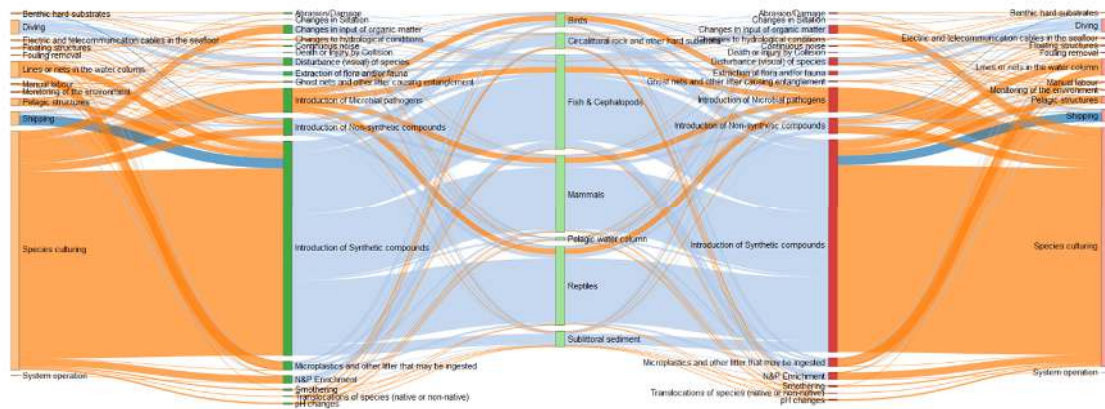


C. Decommissioning NL

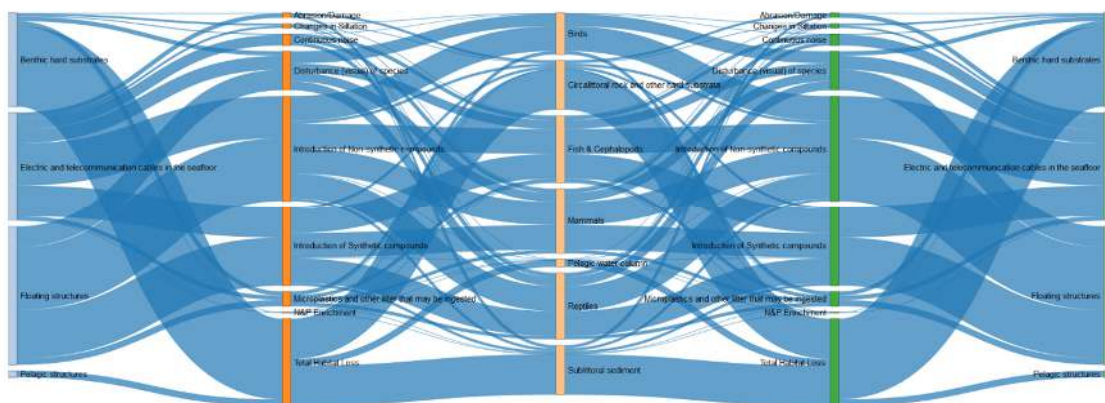
Figure 12. Sankey diagram showing the flow of Impact Risk on ecosystem components in the Dutch pilot for the Installation phase (top), Production phase (middle) and Decommissioning phase (bottom). The ecosystem components are shown in the middle of the Sankey, with the SU activities at the left (IR flowing from left to right) and the MU activities at the right (IR flowing from right to left). Colors indicate the differences between IR from SU and MU: orange = relatively large differences; light blue = relatively small differences; blue = no difference in IR between SU and MU.



A. Installation GR



B. Operation GR



C. Decommissioning GR

Figure 13. Sankey diagram showing the flow of Impact Risk on ecosystem components in the Greek pilot for the Installation phase (top), Production phase (middle) and Decommissioning phase (bottom). The ecosystem components are shown in the middle of the Sankey, with the SU activities at the left (IR flowing from left to right) and the MU activities at the right (IR flowing from right to left). Colors indicate the differences between IR from SU and MU: orange = relatively large differences; light blue = relatively small differences; blue = no difference in IR between SU and MU.

### 2.2.3. Nature enhancement

The assessment of potential benefits for nature can be demonstrated by assessing the contribution to the abundance of hard substrate benthos by Nature Restoration (i.e., oyster reefs) and the scour protection layer and monopiles of OWFs. The contribution is based on the extent of the introduced habitat, the resilience of the EC (similar to the CIA), and the abundance at the start ( $t = 0$ ). The abundance at  $t=0$  is assumed to be 50% for the oyster reefs and 1% for the hard substrates of OWF (abundance cannot be 0 as this does not allow any growth). These are then combined with the reductions of hard substrate habitats (through IRs) in the North Sea to estimate the potential net contribution of Nature restoration and OWF to hard substrate biota (Figure 14). Monopiles are defined as an additional extra hard substrate in the Aquacross approach. In our approach the installation of hard substrates leads to soft substrate loss in the installation phase and to hard substrate increase in the operational phase as in this period the hard substrate is colonised with the typical benthos associated with the hard benthos (depending also on the zonation in relation to water height). Since no other activities were defined as extra hard substrate, no other activity-pressure combinations exert a positive IR. For circalittoral hard substrate, Nature Restoration contributes most to the enhancement of biota. Because Nature Restoration involves constructing oyster reefs on the seafloor, it does not contribute to the enhancement of infralittoral and/or littoral habitats. The monopiles however, provide artificial hard substrate habitat throughout the water column and therefore also artificial infralittoral and/or littoral habitats. Thus, for these latter habitats wind farms have a contribution to the enhancement of biota whereas oyster reefs have not.

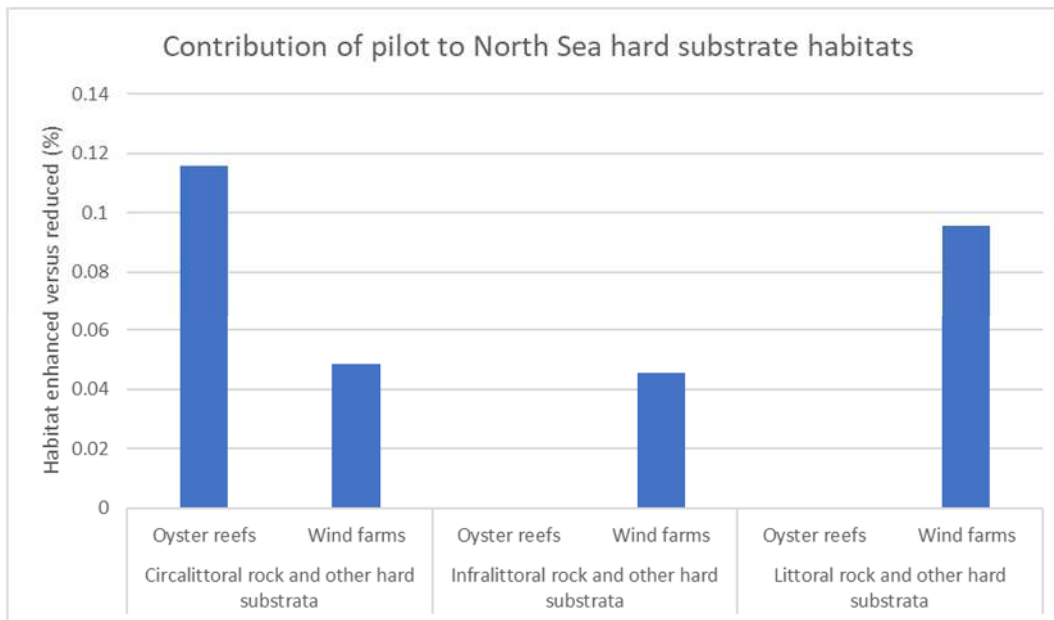


Figure 14. The relative contribution of the Belgian Pilot (in single-use, operational phase) to the hard substrate habitats in the North Sea demonstrating the nature enhancement of additional hard substrates as provided by nature restoration (oyster reefs) and the monopiles and anti-scouring (wind farms).

### 2.2.4. Multi-use compared to single-use

To compare for each pilot SU versus MU, the relative reduction in IR was assessed by subtracting MU from SU and dividing this difference SU (relative difference in IR) for each pilot. The results are shown in percentage reduction of IR per ecosystem component for each of the five pilots in **Error! Reference source not found.** **Error! Reference source not found.** to **Error! Reference source not found.** **Error! Reference source not found.**. Note that, because IR is an estimate of the expected change in state of the various ecosystem components from an average year of activity for as long as the activity lasts. Once the activity stops recovery from some of the pressures (depending on their persistence) may occur.

For Belgium (Figure 15**Error! Reference source not found.**), the highest reduction in IR (ca 40% for fish and mammals) is achieved in the installation phase. This reduction is related to the pre-installation activities (Figure 9). Also, for decommissioning considerable reduction in IR is shown, with the highest reduction (ca 20%) for circalittoral rock

and other hard substrate and sublittoral sediment. The operational phase shows considerably less reduction compared to installation, with nearly 3% at most for fish. This reduction is an annual value (3% reduction each year, not only on one occasion), hence it represents an important relative change.

In contrast, for Germany (Figure 15) there is very little impact reduction (< 1%) in the installation phase and decommissioning phase. The pre-installation activities, which showed a relatively high reduction for the Belgian pilot, are not expected to change in MU compared to SU for the German pilot (Figure 10). However, during the operational phase reduction in IR is estimated to reach a maximum of ca 5% for fish.

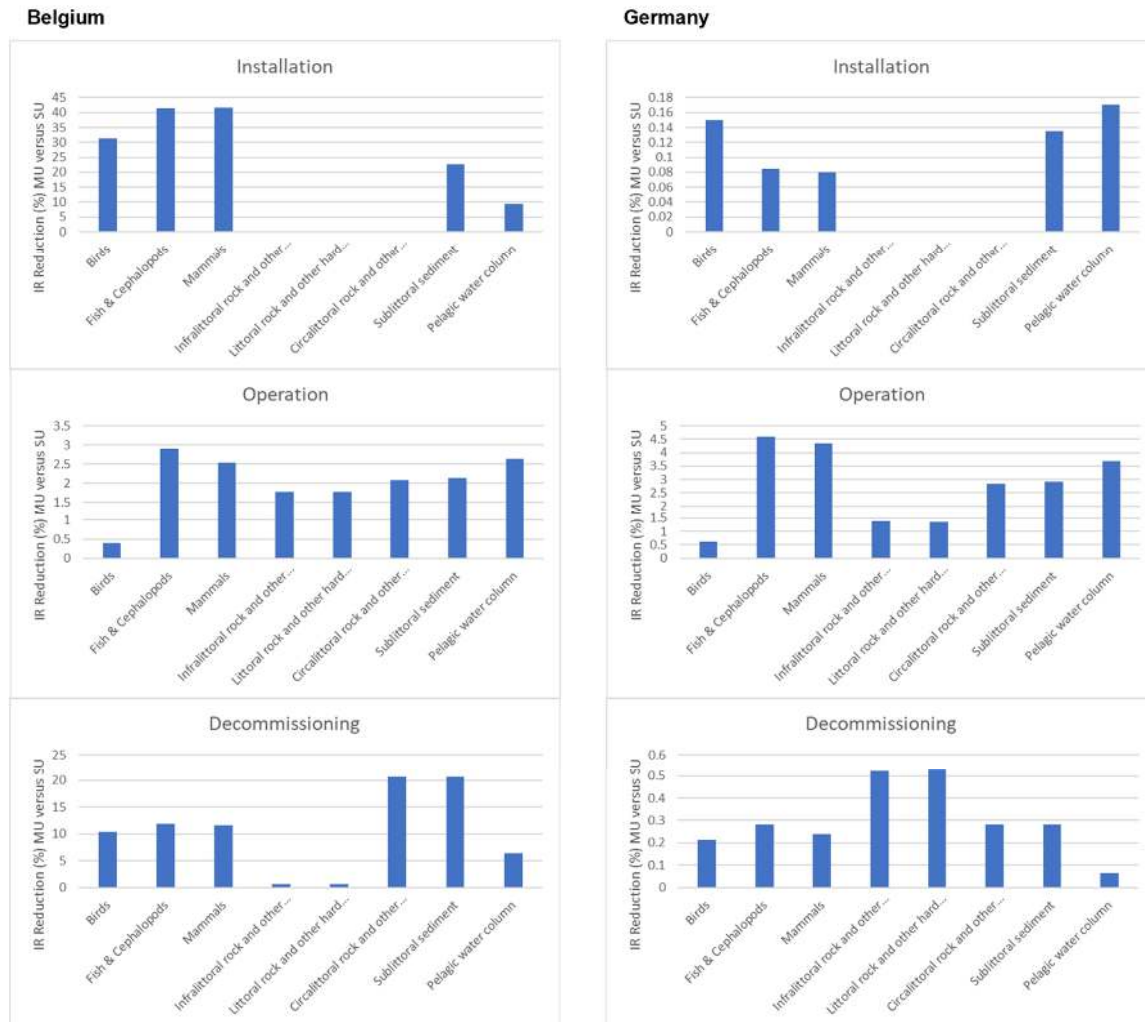


Figure 15. Reduction (%) in Impact Risk for each Ecosystem Component by activities in multi-use design as compared to single-use design for the Belgian pilot (left) and German pilot (right) for all three phases.

In the Danish case (Figure 16Error! Reference source not found.Error! Reference source not found.), impact reduction in the installation phase is minor (ca. 1% at most). In the decommissioning phase there is no reduction expected. The operational phase, however, shows a relatively high impact reduction (compared to Belgium, Germany, and Greece), with ca. 12% at most for (littoral and infralittoral) rock and other hard substrate.

For the Netherlands (Figure 16Error! Reference source not found.), highest reduction in IR (ca 35% for fish and mammals) is achieved in the installation phase, which is similar to the reduction shown for Belgium (most by sharing the infield and export cables). The decommissioning phase shows however very little impact reduction (< 1%). During the operational phase reduction in IR is estimated to reach a maximum of ca 14% for fish and mammals.

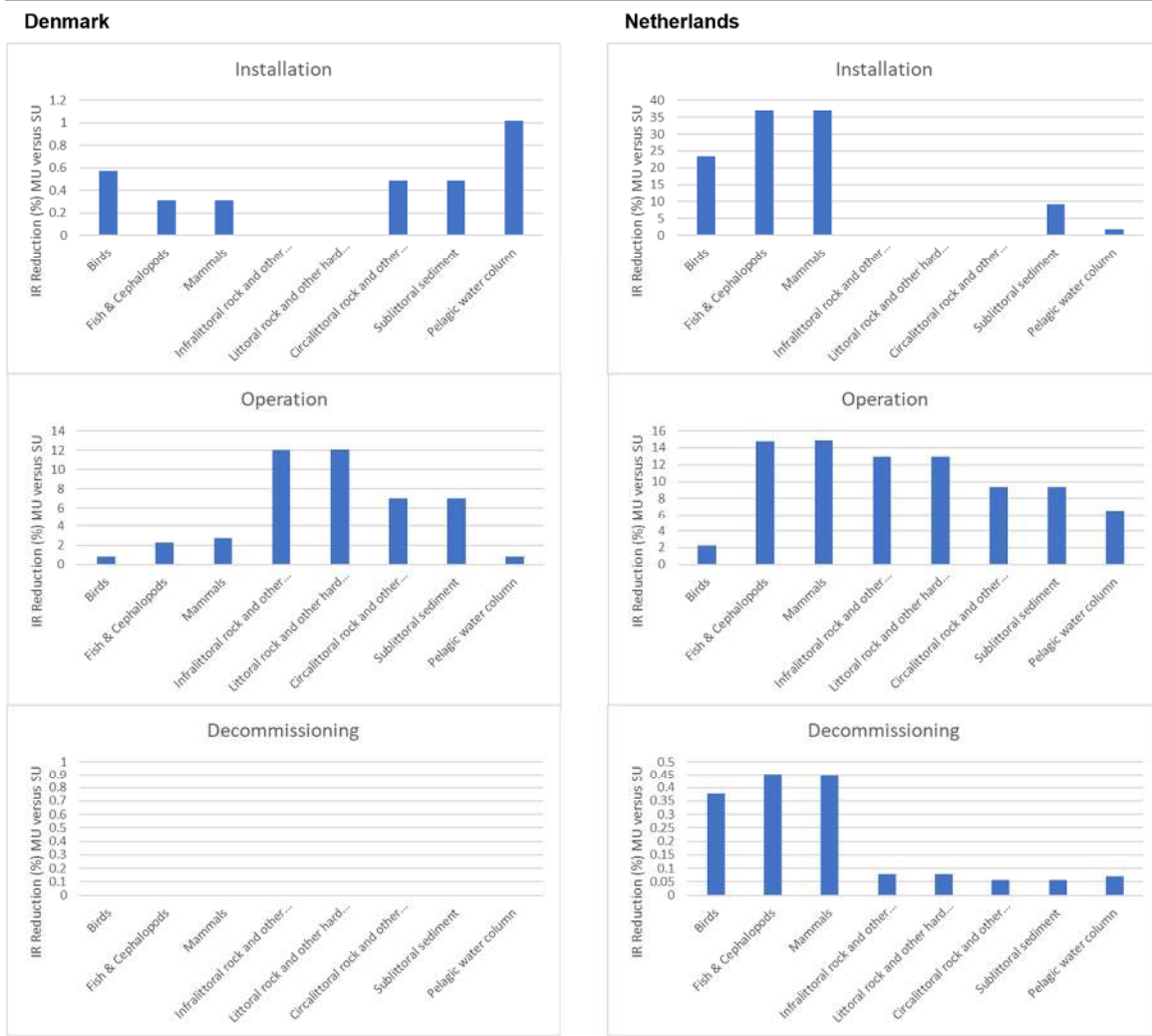


Figure 16. Reduction (%) in Impact Risk for each Ecosystem Component by activities in multi-use design as compared to single-use design for the Danish pilot (left) and Dutch pilot (right) for all three phases.

In Greece (Figure 17Error! Reference source not found.), impact reduction is only expected for the operational phase, with a maximum of ca 2.5% for birds.

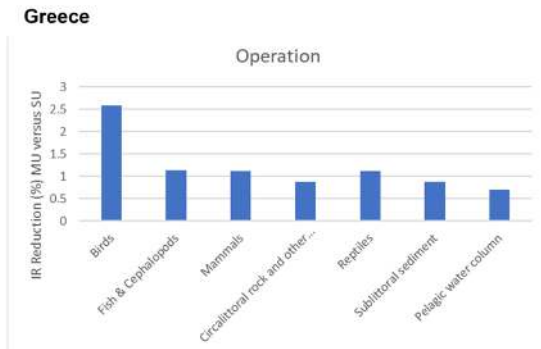


Figure 17. Reduction (%) in Impact Risk for each Ecosystem Component by activities in multi-use design as compared to single-use design for the Greek pilot for the Operation phase.

It should be noted that these impact reductions are relative values and hence do not represent an absolute reduction of impact. This is better illustrated by the Sankey diagrams (Figure 9 to Figure 13). The estimated absolute reduction of IR of MU compared to SU is most striking for the installation phase in Belgium (Figure 9) and the Netherlands (Figure 12) and related to the IR of impulsive noise from pre-installation actions on mammals and fish. Although lower reductions are expected for the operational phase, the reduction is annual, so repeated each year which means for the operational phase a yearly reduction during the exploitation period (typically from 15 years in the case of OWFs).

## 2.3. Evaluation of multi-use

### 2.3.1. Single-use compared to baseline scenario

Part of this evaluation is a comparison of pilot activities with baseline activities (reference scenario on the North Sea where only fishing, shipping, and recreational activities are taking place). The results of this CIA show that the Impact Risk from pilot activities (single-use) is lower than the Impact Risk from baseline activities. Therefore, in the case of all baseline activities being excluded from the considered area, the total IR in the operational phase can be expected to be reduced when compared to the situation prior to the pilot development.

### 2.3.2. Single-use versus multi-use

For all pilots, IR is expected to reduce in MU compared to SU. Relative IR reductions are most pronounced for ecosystem components in the installation phase, followed by the decommissioning phase (both just occasionally). Small yearly reductions are expected in the operational phase (but lasting the full operational lifespan of the initiative, an anticipated 15 years or more).

**Installation phase:** IR reduction in the installation phase is highest for the ecosystem components: fish, mammals, birds, and sublittoral sediment. The highest relative reduction (ca. 40% for fish and mammals) is estimated for the Belgian pilot in the installation phase. Also, for the Netherlands, a relatively high reduction of IR is estimated for the installation phase. For other pilots, the installation phase shows no or very little reduction. This is because for these pilots the extent and duration of actions are either identical or similar in MU compared to SU.

**Operational phase:** During operations, all pilots show reductions of IR in MU compared to SU. Highest reduction is shown for the Netherlands which is estimated to reach ca 14% for fish and mammals mainly related to lines or nets in the water column. Also, in Denmark a relatively high reduction is expected, with a max of ca. 12% for (littoral and infralittoral) rock and other hard substrate mainly related to diving. For Belgium and Germany, the highest reduction is estimated for fish at nearly 3% and 5%, respectively mainly related to species culturing. In Greece, impact reduction is only expected for the operational phase, with a maximum of ca 2.5% for birds which is also mainly related to species culturing. Note that reductions are relative and hence are not a measure of absolute reduction of IR. The absolute reduction in IR is very minor. Because reported reductions are annual, they may accumulate during the operational phase to higher numbers than the incidental high reductions in the installation and decommissioning phase.

**Decommissioning phase:** IR reduction in the decommissioning phase varies considerably over the pilots with relatively high reduction for Belgium (ca 20% benthic habitats), very little reduction (<1%) for Germany and the Netherlands and no reduction for Denmark and Greece. As was also noted for the installation phase, for the decommissioning phase of these pilots the extent and duration of actions are either similar or identical in MU compared to SU.

### 2.3.3. Benefits per ecosystem components

Highest reduction in impact is expected for fish and mammals (ca. 40% in the installation phase of the Belgian pilot) but also for birds and sublittoral sediment impact reduction is relatively high (ca. 30% and 20%, respectively). This is because several actions for this phase and pilot are intended to be shared in MU including a reduction in time resulting in less pressure (visual disturbance, noise etc.) and subsequently less IR, especially for the species groups.

Also, during operations in the Belgian, Dutch and German pilots highest reduction is expected for fish and mammals. In Denmark highest reduction is expected for benthic habitats. This pilot integrates the touristic activities for diving,

climbing and fishing with the wind farm facilities so that interaction with the seafloor (e.g., anchoring) is greatly reduced. In Greece, impact reduction is highest for birds.

Highest absolute reduction of impact is also observed for mammals and fish and related to the noise from pre-installation actions in the Belgian and Dutch pilots.

#### 2.3.4. Assumption for reduction in multi-use

As described in the methodology, it is assumed that combining activities in a multi-use project may lead to a reduction in their cumulative IR. The combination may involve sharing space (reflected in the area extent) or time (reflected in frequency and/or duration of specific actions). The expected reduction in time has been estimated by the partners responsible for each pilot. The expected reduction in extent has been assessed by assuming co-existence is possible for only some actions (Table 4).

Yet, in practice the combination of activities and sharing of time, space, infrastructure, and resources, is challenging. Within the pilots of UNITED, reasonable assumptions for a combination of activities in future commercial MU projects were made, based on what is feasible with current technology, knowledge, and regulations. Reasons for not being able to combine actions in a MU context may fall under the following categories: a) the action is only relevant for one of the activities (and thus does not apply for MU) or; b) the action involves structures/installations/facilities which will not be shared by different activities, e.g. due to practical limitations such as safety regulations, insurance policies and/or permit conditions.

While actions falling under category a) are likely to remain un-sharable in the close future, actions falling under category b) may be possible in the future with the adaptation of regulations and development of new tools (insurances, permits) and technology (infrastructure designed specifically to enable MU projects). To account for this future situation, where MU might be brought to a next level, a hypothetical scenario was designed, called the 'Potential optimal' scenario, in which actions falling under the b) category are possible (see Annex 4 for a table defining shareable actions and comparison with the realistic scenario in current settings).

Figure 18 displays the expected IR reduction during the operation phase of the Belgian pilot in the potential optimal scenario (hypothetical, blue bars) and in the realistic scenario (pilot, orange bars), on each considered ecosystem component.

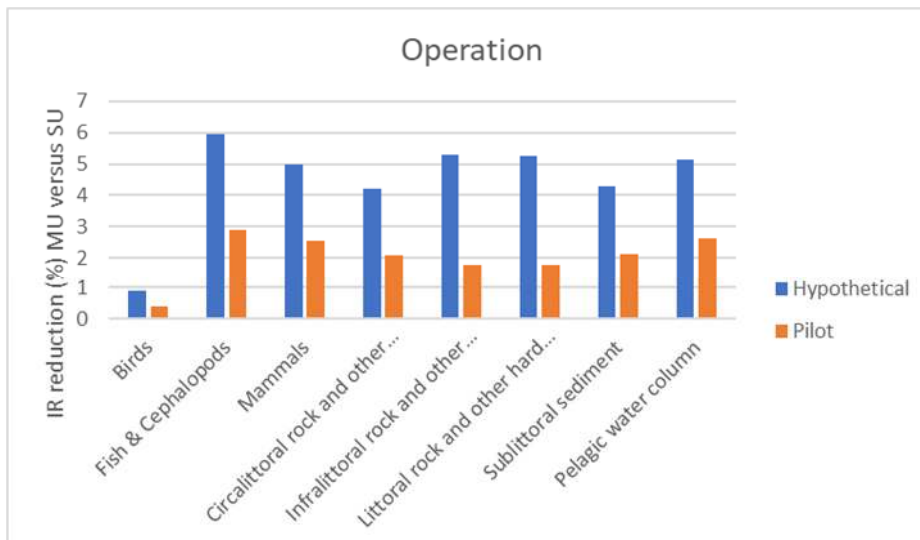


Figure 18. Reduction (%) in Impact Risk for each Ecosystem Component by activities in multi-use compared to single-use for the Belgian pilot (operational phase). Two different assumptions are used: pilot scenario assuming no sharing of structures (used for all results in this study) and hypothetical (potential optimal) scenario assuming sharing of structures is allowed and feasible.

---

## 2.4. Conclusions and discussion on the CIA of multi-use

### CIA method developments

In this study, the CIA method SCAIRM according to Piet et al. (submitted) and previous work (e.g., Borgwardt et al., 2019; Knights et al., 2015) has been applied to assess the UNITED pilot activities. Considering the method has previously been applied for studies on relatively large spatial scales (i.e., regional seas), this is the first application at the local scale. Additional details have been applied to define the pilot activities according to a list of actions. Also, this is the first time that the SCAIRM method has been used to assess the change in cumulative impact when integrating multiple activities and functions at a designed small spatial scale (i.e., multi-use). For this latter application, the method has been extended to include the co-existence of actions in space and time within each pilot. Another methodological addition developed within UNITED is the ability to assess the contribution of nature enhancement to the abundance of hard substrate benthos.

This study demonstrates that the application of the SCAIRM method allows to identify the change in cumulative impacts by multi-use as compared to single-use for pilots of various designs, including the contribution of nature enhancement to hard substrate habitats.

### Highest IR

In general, for single-use as well as multi-use, the highest IR is found in the operational phase, followed by the installation phase. Also, for single use as well as multi-use, the highest IR received by ecosystem components occurs in either birds or fish and mammals, depending on the pilot design.

### Highest contribution to nature enhancement

The highest contribution to the abundance of hard substrate benthos was found for the application of oyster reefs. The OWF monopiles introduce artificial hard substrate covering the total vertical dimension of the water column, thereby especially contributing to the infralittoral and littoral hard substrate benthos (that are the shallowest hard substrate habitats).

### Pilot compared to baseline

The results of this CIA show that the IR from pilot activities operated in SU is lower than from the initial baseline activities (fishing, shipping, recreation) they are replacing. Therefore, it can be expected that the total IR in the operational phase of the pilot area will be reduced compared to the situation prior to the pilot development, assuming the baseline activities will be prohibited in the study area.

### MU compared to SU

For all pilots IR is expected to reduce in MU compared to SU. IR reductions are most pronounced for specific ecosystem components in the installation phase, followed by the decommissioning phase. Rather limited reductions are expected in the operational phase.

Highest absolute IR reduction by application of MU instead of SU is expected for subsequently fish, mammals, birds, sublittoral sediment, other habitats.

The expected reduction in IR has been assessed by assuming co-existence is possible for only some actions. However, when more actions are combined including sharing of structures, higher reductions in IR can be achieved. It is thus important to consider how the activities will be conducted in MU compared to SU. In other words, the MU needs to be clearly defined, especially in spatial and time dimensions. The list of actions describing the potential combinations for each pilot, together with the flows of IR (IR caused by actions via pressures to ecosystem components) can help to identify the most promising actions to reduce IR by MU.

### 3. WIDER CONSEQUENCES OF MULTI-USE

Coming back to the UNITED Assessment Framework, the CIA achieved step 1 and part of step 2. To complement it, the positive wider consequences of ocean multi-use projects are further developed in this section. This is to highlight the potential added value of multi-use through environmental benefits that could be brought by a multi-use project. The CIA has highlighted that impact risks could be reduced on certain ecosystems components, mostly for fish and mammals, that an increase in hard substrate habitat could be achieved, although this would be an artificial hard substrate, that some combination of uses bring more impact risk reduction than others (the combinations in the Belgian and Dutch pilot resulted in highest impact risk reduction), and that some phase (mainly installation on the short term and operation on the long term, considering a lifetime of >10 years) would bring more impact reduction than others.

While a reduction in negative impact certainly is a major argument to implement multi-use projects instead of single-use ones, the potential of generating positive environmental impacts is equally essential. Positive impacts occur when restoring threatened habitats, providing protection for biodiversity, enhancing ecosystem functions, or offering a more eco-friendly food production system for example. These types of wider impacts are discussed in the following section. They are meant to support decision-making as to what type of multi-use to implement, based on contextual priorities (restoring habitat vs raising social awareness on environmental issues for example). They can also support applications by informing on what ecosystem services are provided or what European environmental strategies would benefit from ocean multi-use. This analysis participates in the assessment of the meaningfulness of impacts, as envisioned by step 2 of the UAF.

#### 3.1. Method

The wider consequences of ocean MU were assessed from a literature review and through a workshop session with UNITED’s pilot leads during a project general assembly in February 2023.

Quantification of these consequences was not possible at this stage. Some of them are not quantifiable, while others might be, but data is currently lacking. As an alternative, the identified indirect impacts of the pilots were analyzed based on the following criteria, to assess their significance:

- **Ecosystem health:** assessment of the impact’s contribution to ecosystem health, based on literature review. Values: high, medium, low.
- **EU policies:** assessment of the impacts’ contribution to European environmental goals and strategies. Values: name of the goal/strategy to which the impact contributes.
- **Ecosystem services:** type of ecosystem services provided by the impact, based on Culhan et al. (2018). Values: provisioning services, regulating services, cultural services.

*Table 6. Criteria for analysis of indirect impacts’ significance of UNITED’s pilots*

	Pilots	MU scenarios	Ecosystem health	EU policies	Ecosystem services	Optimization
Impact 1						
Impact 2						
....						

In addition to these criteria, the pilots and multi-use scenarios concerned by the impacts are defined, and optimization measures are proposed. Optimization measures are recommendations, based on literature review and the project’s experience, to ensure that the positive impacts take place and that they are maximized.

### 3.2. Assessment

Table 7. Analysis of potential wider consequences of UNITED's pilots.

Impacts	Pilots	Mu scenarios	Ecosystem health	EU policies	Ecosystem services	Optimization
Oyster reef restoration	BE	Rest. & OWF Rest., OWF & Aqua	High	<b>Green Deal</b> Nature Restoration Law <b>MSFD</b> GES D1	Provisioning	Adapted decommissioning Nature inclusive design
Biodiversity increase	BE NL DE	OWF & Rest. OWF & LTA OWF, Rest. & Aqua	Medium	<b>MSFD</b> GES D1	Provisioning	Adapted decommissioning Nature inclusive design
Nutrient cycling	BE NL DE	OWF & Rest. OWF & Aqua OWF, Rest. & Aqua	High	<b>MSFD</b> GES D5	Regulation and maintenance	Adapted decommissioning Nature inclusive design
Carbon sequestration	BE NL DE	OWF & Aqua OWF, Rest. & Aqua	High	<b>Green Deal</b> Sustainable Carbon Cycles	Regulation and maintenance	Adapted decommissioning Nature inclusive design
Commercial fish species increase	BE NL DE	OWF & Rest. OWF & Aqua OWF, Rest. & Aqua	Low	<b>MSFD</b> GES D3	Provisioning	Adapted decommissioning Nature inclusive design
Sustainable food production	BE NL DE GR	Aqua & OWF Aqua & Tourism	High	<b>Green Deal</b> Farm-to-Fork Strategy Sustainable Blue Economy	NA	Electrical fleet Biodegradable materials
More space for conservation	BE NL DE	OWF & Rest. OWF & Aqua OWF, Rest & Aqua	High	<b>Green Deal</b> Biodiversity Goals	NA	Depends on policymakers
Reduction of conflicts over space use	BE NL DE	OWF & Rest. OWF & Aqua OWF, Rest. & Aqua	Low	<b>MSP Directive</b>	NA	Depends on policymakers
Increased social acceptance of OWF and LTA	BE NL DE DK GR	Aqua & Tourism OWF & Tourism OWF & Rest. OWF & Aqua OWF, Rest. & Aqua	Low	<b>Green Deal</b> in general	NA	Good communication

**Aqua:** Aquaculture; **BE:** Belgium; **D:** Descriptor; **DE:** Germany; **DK:** Denmark; **GES:** Good Environmental Status; **GR:** Greece; **MSFD:** Marine Strategy Framework; **NL:** Netherlands; **OWF:** Offshore Wind Farm; **Rest.:** Restoration

For a detailed analysis of the contribution of ocean multi-use to the listed European Environmental goals and strategies, please refer to Deliverable 8.3 of UNITED (Van Gerven et al., 2023).

### 3.3. Description of potential wider consequences

#### ➤ Oyster reef restoration or creation

In the North Sea, the seabed is mostly made of soft sediments (sand and silt) interrupted by gravel bed patches. In the past, before 1900, hard substrates were often found in the North Sea, composed of biogenic reef of European flat oysters and remnants of trees and vegetation. Yet these habitats were largely destroyed and removed by human activities, leaving little chance for hard substrate fauna to survive, and resulting in a heavy loss in biodiversity and keystone species (Lengkeek et al., 2017).

Restoring European flat oyster reefs in the North Sea can only be envisioned in areas where no disturbance of the sea floor occurs, for they are sensitive formations that build over long periods of time. Until recently, no such area existed in the North Sea, hence reef restoration was not possible, but offshore wind farms that exclude fishing

**activities now present themselves as solutions to this issue.** In addition, scour protections offer ready-to-use habitat, made of natural rocks, to be colonized by European flat oysters and on which a reef can develop.

The ideal scenario would be to have a historical habitat of oyster reef nearby the multi-use project, that would rebuild thanks to the oysters added in its proximity. By bringing oysters to recolonize historical habitats, a true restoration program could be envisioned. In the absence of such a situation, as areas allocated to multi-use may not have taken that aspect into consideration, careful research and planning may justify habitat creation to support a broader restoration effort. This should, however, be done with caution and with an extensive investigation of the consequences of modifying the natural occurrence of that habitat, losing the habitat and features that would naturally occur in the considered area.

➤ *Biodiversity increase*

In the future, extensive protection measures against high-impact activities have the potential to greatly benefit large areas of the North Sea, as offshore wind farms restrict bottom trawling fisheries and often prohibit all forms of fishing activities within their boundaries. Sensitive and slow-growing macrofaunal species, vulnerable to bottom-fishing activities and declining over the past century, are benefiting from the offshore windfarms' protection where they are found in higher abundance after only three years of fishing exclusion (Coates et al., 2016). The protection from fishing benefits higher trophic levels as well, with a potential spill-over effect to compensate, if only partially, the loss of fishing grounds for the fishing sector (Halouani et al., 2020). The fishing exclusion effect of wind farms can be further enhanced through the integration of low-trophic aquaculture practices. By implementing lines suspended between the turbines, the fishing exclusion becomes absolute, making even illegal fishing highly improbable.

**Wind farms have been observed to have a positive influence on biodiversity due to the phenomenon known as the artificial reef effect.** This effect is facilitated by the presence of scour protection and monopiles, which provide a solid substrate habitat and create an intertidal zone that would not exist otherwise. The newly formed artificial reef rapidly and extensively attracts sessile fauna, pelagic and demersal fish, and leads to an increased density of large decapods (Dannheim et al., 2020). Numerous studies have consistently found higher fish abundance within offshore wind farms compared to reference areas, with some research also indicating greater species diversity. Fish will gather for feeding, shelter, reproduction, and meeting point (Degraer et al., 2020), in turn attracting larger predators such as sharks and marine mammals. Artificial structures, in general, tend to augment the abundance of hard-bottom species and enhance fish diversity in the surrounding vicinity (Glarou et al., 2020). They can also support connectivity at a larger scale, providing larvae to colonize other areas and receiving larvae from other areas (Tidbury et al., 2019; van der Molen et al., 2018).

**Marine mammals are similarly attracted to the turbines and scour protection to feed.** In the North Sea, tagged seals with were seen specifically feeding in between turbines (Russel and al., 2014) and porpoises were in higher occurrence in a Dutch area compared to a reference area (Scheidat et al., 2011) and found in abundance in the German pilot of UNITED, likely attracted by an increased food availability.

With ocean multi-use, these described positive effects on biodiversity are expected to be amplified when offshore windfarms are combined with low-trophic aquaculture. Low-trophic aquaculture can take several forms, but often consist in lines and nets hanging at the water surface and/or a few meters below. Seaweed will typically hang closer to the surface to benefit from optimal light exposure, while shellfish can hang of float lower in the water column, on lines, nets, baskets, tables, etc. – many systems exist and remain to be tested.

While not all of these structures are hard, they are still likely to provide similar functions as the structures found in offshore windfarms and platforms. In the United States for example, dolphins were seen hunting close to mussel farms (Price et al., 2017), likely attracted by fish feeding from the farm. In Norway, kelp farms have been found to provide habitat and shelter to biodiversity, in a similar way than wild kelp forests. Like artificial reefs, seaweed aquaculture offers surface for biodiversity to settle, as well as food source, shelter, nursery and meeting point for fish, birds, mammals, and more (Bekkby et al., 2023; Jansen and Tonk, 2018). The artificial kelp forest, however, presented lower taxa abundance and richness, and lower species diversity (Bekkby et al., 2023). This finding is coherent with what was found on the windfarms: less diversity on windfarms artificial substrate than on natural reef, in the long term (Coolen et al., 2020; Degraer et al., 2020). While this should be kept in mind as a reason to never

use artificial reefs as replacements of existing natural ones, artificially introduced habitats can still support biodiversity, connectivity, and ecosystem health as an addition and in combination with well-protected natural habitats.

Figure 13 shows a simplified representation of the artificial reef, based on the ecosystem components that were used to conduct the CIA in section 1 of this report, and reproduces a linkage approach to illustrate possible secondary impacts of an ocean multi-use project. The impacts displayed are interactions between ecosystem components (habitats and live organisms), represented by colored arrows. The green arrows indicate trophic links, and the blue arrows represent non-trophic links, such as shelter, meeting point, habitat provision, or sedimentology changes.

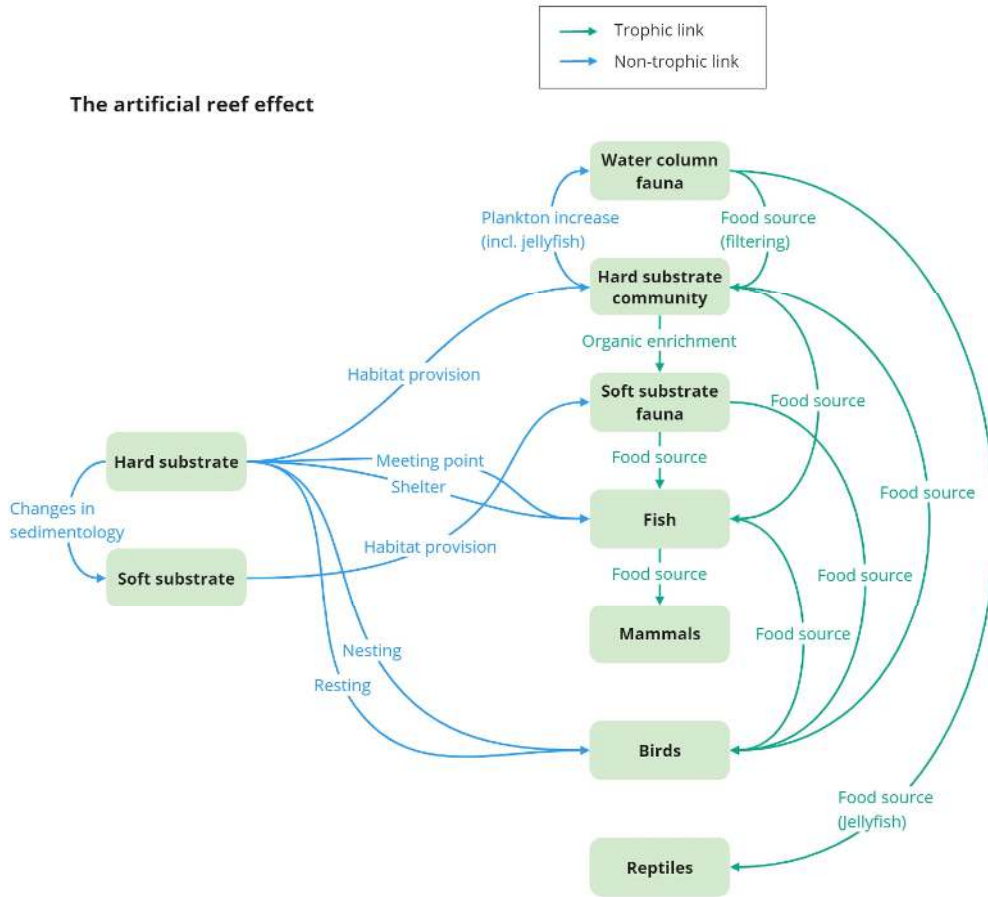


Figure 19. Simplified representation of the artificial reef effect in the context of the UNITED ocean MU scenarios.

➤ *Nutrient cycling*

Benthic fauna that develops on artificial hard substrate is largely composed of suspension feeding organisms, such as mussels, barnacles, anemones, etc., that can help improve water quality by removing excess nutrients such as nitrogen and phosphorus from the water. These nutrients are embedded in organic matter, incorporated into the filter feeders’ tissue and excreted as waste, which can contribute to nutrient cycling in aquatic ecosystems. In the case of shellfish aquaculture, when the organisms are harvested, the nutrients are removed from the marine environment. **Mussels is the most likely low-trophic aquaculture to be developed in the North Sea and, as they filter large volumes of water, being able to play an important role in regulating nutrient levels in aquatic environments.**

**Seaweed can effectively remove nutrients, making them ideal for mitigating the nutrient overload caused by fed aquaculture** or other sources of nitrification, and they can be cultivated without the need for fertilizers and agrochemicals. As photosynthetic organisms, seaweeds are the only component in aquaculture systems that produce oxygen, while other components, whether fed or organic, consume oxygen. This characteristic of **seaweeds helps**

---

**prevent coastal hypoxia.** Furthermore, through their photosynthetic activity, **seaweeds absorb carbon dioxide**, thus participating in carbon sequestration and increasing seawater's pH, therefore **potentially reducing ocean acidification** (Buck et al., 2017).

For aquaculture, it depends on circumstances: E.g., the Finfish and Shellfish culturing exert smothering and input of extra organic matter. In the Aquacross approach, these are pressures having an IR reducing the quality of the Benthic Habitat (Soft and Hard). That is true on the regional level but on the local level, it depends on aspects like total input, background concentrations, standing stock, and currents (Buck et al., 2017). Depending on circumstances, the input of extra organic material could be detrimental (e.g. suffocating or consuming oxygen) or beneficial (adding additional food) or having no impact due to the high current speeds. Bridger et al. (2022) demonstrated a habitat restoration and improvement as the result of the marine snow of pseudo faeces of mussel aquaculture.

➤ *Carbon sequestration*

Both seaweed and shellfish aquaculture participate in increased sedimentation with organic waste (feces, dead bodies) deposited on the seafloor where they constitute a food source for other benthic organisms and, over time, may sink into the sediments, increasing carbon storage (Buschmann et al., 1996; Degraer et al., 2020; Eng et al., 1989; Jones et al., 2022; Zhang et al., 2009). If the seafloor remains undisturbed, sediments can constitute a considerable carbon sink (De Borger et al., 2021).

**Seaweed, both wild and cultivated, act as an important mechanism for the removal of CO<sub>2</sub> from the atmosphere**, with highly autotrophic communities estimated to take up 1.5 Pg per year globally (Krause-Jensen and Duarte, 2016; Duarte et al., 2017). Additionally, seaweed communities produce a significantly greater amount of organic matter through photosynthesis compared to what is consumed through respiration in the ecosystem. As a result, they play a significant role in capturing a substantial amount of CO<sub>2</sub> in marine vegetated habitats (Duarte et al., 2017). Carbon sequestration from seaweed aquaculture happens locally, just underneath the farm, with dead bodies accumulating on the seafloor, or at a larger scale with lateral transportation of seaweed detritus to carbon sinks (Ross et al., 2023).

➤ *Commercial fish species increase*

**Commercial fish species may increase thanks to ocean multi-use, through the artificial reef effect, known to occur in offshore windfarms and expected to increase when combined with low-trophic aquaculture.** The following commercial fish species have been found to be attracted to the North Sea's windfarms (non-exclusive list): Atlantic cod (*Gadus morhua*), European seabass (*Dicentrarchus labrax*), black seabass (*Centropristis striata*), Atlantic mackerel (*Scomber scombrus*), Atlantic horse mackerel (*Trachurus trachurus*) and plaice (*Pleuronectes platessa*) (Bergström et al., 2013; De Broger et al., 2021; Degraer et al., 2020; Degraer et al., 2021; Reubens et al., 2014; Wilber et al., 2020). With interdiction to conduct fishing in the wind farms, which would be reinforced by the presence of low-trophic aquaculture, a spill-over effect could benefit commercial fish stock.

➤ *Sustainable food production*

**Low-trophic aquaculture, such as the cultivation of shellfish and seaweed, has been found to have a smaller ecological footprint compared to other forms of aquaculture** (Jones et al., 2022). This method offers environmental benefits as it eliminates the need for irrigation and does not need the conversion of additional arable land, thus preserving vital ecosystem services (Buck et al., 2017). Unlike farmed plants and animals, seaweed and shellfish can grow without the need for external feeding during their sea-based cultivation, resulting in reduced environmental and economic costs. Interestingly, mussels can even attach themselves naturally to longlines, eliminating the need for hatcheries on land. Consuming organisms from lower trophic levels aligns with the principle of a more efficient food system (Van der Meer, 2020). Energy and resources diminish as you ascend the food chain, making lower trophic organisms a preferable choice (Jones et al., 2022).

Furthermore, when appropriately planned and managed, low-trophic aquaculture can contribute to the preservation and proper functioning of marine ecosystems. It serves as a habitat for diverse marine life and aids in the removal of excessive organic matter from the water column, thus helping to mitigate the impacts of eutrophication.

Finfish aquaculture, in contrast to low-trophic aquaculture, does not offer as many environmental benefits and has a higher ecological footprint (Jones et al., 2022), in part due to the need for external feeding. However, local food production plays a crucial role in establishing a sustainable food system. **Coastal finfish aquaculture, which supports local consumption, is likely to have a lower environmental impact compared to importing farmed fish.**

As the demand for animal protein continues to grow, most wild fish stocks are unable to meet the requirements, making fish aquaculture a potential solution for feeding current and future generations. Integrating fish farms with tourism activities can enhance visibility and build trust in aquaculture, which often suffers from a negative reputation. This combination can also generate additional income for local communities, enabling them to adopt sustainable practices in utilizing the marine environment and its resources.

Furthermore, aquaculture products gain value and acceptance when they are recognized by consumers and local residents. The multi-use approach contributes to increasing public awareness of sustainable aquaculture practices and fostering public acceptance, thereby promoting the well-being of rural and coastal communities, and ensuring a dependable supply of high-quality seafood.

➤ *More space for conservation*

**By combining activities in a single area, ocean multi-use can be an efficient tool to ensure more space is available for conservation.** This is especially relevant when considering activities that (1) require a large amount of space and (2) conflict with other uses. Such is the case of windfarms, which require large areas and usually do not allow fishing, shipping or gas extraction for safety reasons. Aquaculture also falls in that category, although the size of farms can greatly vary. In the case of low-trophic aquaculture, only a large farm is considered economically viable, and it cannot allow other activities to take place in its close vicinity.

While these static types of activities at sea conflict with many other uses of the marine environment, they can be combined into a single area, therefore reducing the total amount of space used. The potential benefits are twofold: either the ‘freed’ space is used for other anthropogenic activities, or it is used for conservation purposes as a marine protected area. The second option contributes to biodiversity conservation. **Protected areas are efficient tools to conserve and enhance biodiversity, when correctly designed and enforced.**

➤ *Reduction of conflicts over space use*

The emergence of new commercial activities at sea requires careful spatial planning for European countries. One particular sector that has substantially contributed to the demand for spatial management is the production of renewable energy, specifically offshore wind farms. The ambitious goals for energy transition have led to a substantial increase in utilizing European seas for energy generation. However, the installation of these long-term fixed structures has given rise to conflicts and tensions with other existing uses, such as shipping and fishing, which are often deeply rooted in traditional practices. Similarly, the demand for sustainable food production at sea is on the rise, and this trend is expected to keep increasing with the current European goals and strategy. In this context, combining activities in a single area, especially those that require significant space, becomes essential for the resolution of conflicts over space use at sea. However, **the implementation of multi-use concepts at sea is still in the early stages of development, and Maritime Spatial Planning is expected to play a crucial role in facilitating this transition.** This can be achieved through the designation of specific areas for different functions or by explicitly permitting non-priority activities within zones designated for specific priority activities.

Ocean multi-use, as an innovative practice, opens the road for new forms of cooperation and collaboration between users of the sea. As such, it can be an opportunity to reconcile historically conflicting activities, requiring stakeholder participation and engagement in ecosystem-based Maritime Spatial Planning and sustainable development.

➤ *Increased social acceptance of OWF and LTA*

Offshore windfarm and (lower-trophic) aquaculture are activities that historically have raised concerns by the public. Ocean multi-use can help increase their social acceptance in several ways, such as increased region’s attractiveness, increased transparency, and lower environmental impact.

Ocean multi-use has the potential to significantly enhance the attractiveness of a region through various factors. It creates economic opportunities by integrating multiple activities such as offshore wind energy, aquaculture, tourism, and marine research. This attracts industries and investors, leading to job creation, economic growth, and sustainable development. Multi-use concepts drive innovation and technological advancement, attracting research institutions, technology firms, and skilled professionals. This establishes the region as a hub for marine technologies and fosters a culture of innovation.

**Multi-use approaches prioritize sustainability and environmental stewardship**, enhancing the region's reputation as an environmentally conscious destination. This resonates with environmentally-minded individuals, businesses, and investors. **By incorporating diverse ocean activities, a region can diversify its economic base, reducing dependence on a single industry and fostering a vibrant and diverse business ecosystem. Multi-use concepts also create unique opportunities for recreation and tourism.** For example, combining offshore wind farms with recreational activities appeals to visitors interested in experiencing the coexistence of different ocean uses, stimulating local tourism industries.

Implementing multi-use initiatives encourages collaboration, knowledge sharing, and partnerships across sectors. This collaborative environment attracts experts, researchers, and organizations seeking opportunities to collaborate, exchange knowledge, and contribute to innovative projects. Embracing ocean multi-use enhances the quality of life for residents, offering a dynamic living environment with diverse activities and services. This provides opportunities for leisure, recreation, and cultural experiences, contributing to overall well-being and satisfaction.

Ocean multi-use can also help inform local communities of what happens at sea and lift the veil on some prejudices against certain activities. Visiting wind farms, for example, is the opportunity for the public to get informed on their environmental benefits and witness firsthand that turbines are not that loud. Diving around aquaculture farms also allows the public to see to what extent the environment is impacted, which is a good argument for smaller farms, and witness some of the positive impacts such as dolphins feeding from biodiversity attracted by the farms.

**By leveraging the benefits of ocean multi-use, a region establishes itself as an innovative, diverse, and environmentally responsible destination.** It attracts businesses, investors, professionals, tourists, and residents, enhancing its attractiveness, competitiveness, and sustainability.

### **3.4. Considerations in development and design of OWF for multi-use**

#### **3.4.1. Nature inclusive design**

Nature-inclusive design is an emerging concept increasingly applied when developing the built environment with the purpose to integrate natural systems to support biodiversity, ecosystem services, and human well-being. In the marine context, it focuses on the planning of human activities and the infrastructure they require, explicitly taking account of the natural environment and biodiversity. Examples include creating artificial reefs, installing underwater habitats, adopting sustainable aquaculture practices, and designing offshore wind farms with consideration for marine wildlife.

Multi-use projects could reduce the negative impacts or strengthen their positive impact on biodiversity and ecosystem health by applying nature-inclusive design principles in their conception. This can be done by selecting the least invasive systems, such as minimalist mooring systems, or selecting the right hard substrate, e.g., natural rocks over concrete, to encourage benthic biodiversity growth, or by choosing biodegradable materials.

Artificial reefs can be a nature-inclusive design initiative when infrastructures at sea are intentionally designed to encourage biodiversity settlement. An artificial reef is a human-made structure designed to influence physical, biological, or socio-economic processes related to living marine resources. Its primary goal is to enhance fisheries and conserve marine biodiversity. Artificial reefs can also be used for ecosystem restoration, as well as for socio-economic development and research purposes. Examples include structures purposely built to resemble natural reefs, as well as accidental or repurposed structures like shipwrecks, sunken ships, and offshore oil and gas platforms (Glarou et al., 2020; van der Molen et al., 2018).

Ideally, nature-inclusive design must be incorporated from the very beginning of a project. In the Netherlands, the potential for anti-scouring protection to provide habitat to lobsters and brown crabs, to species of commercial interest, hence to stimulate its growth and subsequent commercial exploitation, was investigated (Rozemeijer & Van de Wolfshaar, 2019; Stelzenmuller et al., 2021). However, this proves more complex than originally expected because scour protections cover only a small percentage of the OWF surface (less than 0.2% in PAWP and Luchterduinen Dutch OWF). The space between the stones of the Dutch wind farms are also too small for a market-grade European lobster (~27 cm long), and a lot, and various types, of food must be available for lobster to profiler

(Rozemeijer & Van de Wolfshaar, 2019). Extensive research and careful planning are essential to successfully exploit the artificial reef effect for commercial purposes.

Another substantial limit is the decommissioning of OWFs, that would lead to the removal of all structures at sea, including scour protection and any benthic community having settled on it. As an alternative, infield cables could be laid in a bed of rocks to provide both protection from breaking and hard substrate as additional habitat (Tonk & Rozemeijer, 2022). Otherwise, reef catalysts could also be installed that lead to attraction and growth of reef-building species with the purpose of creating a natural, self-generating reef (Lengkeek et al., 2017).

#### 3.4.2. Rethinking decommissioning

Approximately 30% of the total installed wind turbine capacity in Europe are older than 15 years (Ziegler et al., 2018), and approaching the end of their service life of 20 years (figure 14). At the end-of-life scenario of an offshore wind farm (OWF) turbine, strategies that developers may opt for include deciding to extend the life of the turbine, repowering or maintaining the ageing asset or decommissioning the turbine (Topham et al., 2019). The latter remains challenging due to regulatory framework, logistics and availability of vessels coupled with largely unexplored environmental impacts (Gill et al., 2018).

As mentioned in the previous section, the OWF structures provide settlement opportunities for a number of marine organisms. However, the downstream effects of decommissioning are not yet properly studied (Tidbury et al., 2020). Nonetheless, it is predicted that the OWF structures which contribute to the artificial reef effect, and thus connectivity of marine species, will be removed (Fowler et al., 2018).

Although particle tracking models have mapped the hydrodynamics of pelagic larval dispersal (Bray et al., 2017; Van der Molen et al., 2015, 2018), large-scale connectivity studies to understand the role of artificial hard substrate removal during the turbine decommissioning process are not yet known. In such a scenario, the precautionary principle should be advocated. Rethinking the decommissioning of OWF turbines may result in approaches that partially or fully leave the (structurally sound) turbine in place, especially if the platform provides benefits to the marine environment (OSPAR, 1998).

#### 3.4.3. Biodegradable materials in aquaculture

Aquaculture operations are far from impact neutral. A prevailing issue in the growing aquaculture industry is the extensive use of plastic materials in, for example, fish cages, buoys, ropes/cords, PVC pipes and shellfish farming bags (Skirtun et al., 2022). The predominant causes of plastic from aquaculture operations entering the marine ecosystem are: extreme weather events, poor waste management protocols, lack of collection facilities at harbors and even deliberate discards. These causes are exacerbated by the low cost of consumable plastics relative to the high cost of recycling (Skirtun et al., 2022). Ultimately, this plastic debris originating from aquaculture operations may choke marine organisms (Kühn et al., 2015), can be ingested by both marine organisms and seabirds, and may break down into microplastics (Huntington, 2019). Specifically, the latter pressure may have a detrimental environmental impact of which the extent far exceeds that of the actual activity due to dispersal by wind, wave, and currents. Furthermore, many of the impacted marine species may be the source of seafood for human consumption with potential health consequences.

With continued population growth and seafood demand, plastic pollution derived from aquaculture operations is also predicted to increase (DNV, 2021). To mitigate this issue, the Global Ghost Gear Initiative (GGGI) have launched a Best Practice Framework (BPF) for the management of aquaculture material (the A-BPF). The A-BPF (GGGI, 2021) is the first document of its kind which provides comprehensive guidance to aquaculture operators on the best methods with which to prevent, remove and mitigate the effects of ghost gear (i.e., materials accidentally or deliberately discarded offshore).

To date, many proposed mitigation measures such as GPS satellite tracking on buoys and other equipment and recovering/collecting all litter lost during storms or which may have fallen over board (De Raedemaeker et al., 2020) have been deemed unfeasible from an economic, financial and time perspective by the industry. Nonetheless, there are several initiatives proposed by both industry and non-governmental organizations (NGOs) to mitigate this issue in the NE Atlantic (Gin et al., 2020), particularly advocating for the use of more weather-resistant and durable materials in aquaculture operations (Hipólito et al., 2020). Examples include flexible installations such as mussel farming longlines and anchors optimized to suit sea currents in the Belgian North Sea or switching to equipment

and gear made from natural or (marine) biodegradable materials such as biodegradable socks in off-bottom mussel culture (GGGI, 2021).

**The use of biodegradable material should not stop at the operational stage of aquaculture practices but should also be applied further down the commercial chain in the form of ecologically-friendly packaging.** Examples include biodegradable mesh for clams, recyclable modified atmosphere packs (MAP) for vacuum sealed mussels (De Raedemaeker et al., 2020), and compostable cardboard fish boxes for salmon (Skirtun et al., 2022). This may be coupled with improved litter/pollutant quantification and stronger implementation of collect, reuse and recycle industry policies. The likeliness of success may be improved with the added appropriate education of staff to sufficiently mitigate and defend against plastic pollution from aquaculture operations.

#### 3.4.4. Electrical fleet

Incorporation of renewable energy such as offshore wind farms and solar photovoltaic technologies into aquaculture projects is key for synergistic and multifunctional ocean use. With the aquaculture industry starting to move offshore into deeper waters where OWF are located, the ocean renewable energy (ORE) (e.g., wave, tidal, ocean current, ocean thermal energy, etc) industry have explored the potential to co-locate these two activities as part of the blue economy initiative. This ocean multiuse model is synergistic and sustainable as it involves both the sharing of marine space between aquaculture and ORE, as well as ORE potentially providing power directly to aquaculture (Freeman et al., 2022). Furthermore, this multiuse reduces competition between the industries and decreases potential detrimental environmental impacts, since the aquaculture operation is fuelled directly with electricity generated by the OWF and not by diesel-powered vessels.

Commissioned by the Blue Economy Cooperative Research Centre (BE CRC), Hemer et al. (2020) modeled the estimated energy required for the operation of Australian Atlantic salmon aquaculture farms to be approximately 6000 kWh/day. This energy demand stemmed from feed barge operations, lighting, venturation (a process of raising dissolved oxygen levels in the water for fish health management purposes), bathing, monitoring, and domestic use. Similarly, Møller (2019) calculated that the average cumulative energy demand across summer and winter operations across the entire Norwegian Atlantic salmon aquaculture industry was approximately 700 kWh/day. Syse (2016) studied the electrical demands of three salmon aquaculture farms across southwest Norway stocked with 150,000 salmon per cage. Here, the feed system (feed barge compressor) was found to account for more than 50% of the daily energy use within the farms. Although larger vessels are typically excluded from OWF areas, and not all aquaculture operations will include the use of a vessel, farms such as salmon aquaculture in Norway, will operate at least with a transport vessel and a working vessel. In the aforementioned studies, the electricity consumption was mapped across multiple components. However, many of these calculations have excluded the transport variable, which is energy intensive. Therefore, **an alternative means by which the synergistic co-location of the aquaculture and OWF industries could be operated as carbon-free as possible, is with the implementation of electrically powered (and not diesel-powered) support vessels.**

Transitioning to an electrically-powered fleet makes use of infrastructure already in place such as the turbine platform and electrical cables, to provide renewable electricity to vessels. **There is a potential to incorporate fully electric or hybridised green propulsion systems into new-build vessels, and also to retrofit existing vessels.** An initiative led by MJR Power in the UK, (as part of the Clean Maritime Demonstration Competition), proposed to design, build, and test an electric charge point situated on a wind turbine. To date, the first harbour trials have been successfully carried out at the Port of Blyth using a crew transfer vessel (CTV) 45harge connection to the 45hargeng point, mooring and charging of the battery bank were successfully validated. Although the maximum charging time for CTVs is two hours, MJR are in development for providing offshore power and charging for larger vessels, including service operations vessels (SOVs), and now prepare for installation on an OWF in the North Sea (MJR Power, 2023).

In this nascent industry, very few case studies or co-location, or ocean multiuse pilot studies exist (Campbell, 2017, UNITED, 2020). More information, including finer-resolution data, about energy demand and the associated energy demand profiles (e.g., daily, monthly, seasonally, for specific stages/processes) for offshore aquaculture operations is needed, as well as comprehensive information on the energy demands of all support vessels, both of which should then be supported by engagement with aquaculture stakeholders. Collectively, this will facilitate partnerships between aquaculture and OWF developers, enabling the transition to hybrid and fully electric vessels for low carbon offshore operations.

---

## 4. CONCLUSIONS

To assess the environmental impact of ocean multi-use, in the form of the pilots of UNITED, the UNITED Assessment Framework was used as a generic guide. For each pilot, a multi-use and a single-use scenario was designed and compared with a generic baseline scenario (reference situation prior to the pilots based on generic activities e.g. fishing, recreation). Because the activities combined in UNITED are of different nature, and likely to cause different impacts on the marine environment, a Cumulative Impact Assessment (CIA) methodology was applied to predict the effect of the different scenarios.

The main findings of this application of the extended CIA in a multi-use EIA context were:

- The extended CIA was able to assess what each of the relevant sectoral activities contribute to the environmental impact in a single-use context.
- Potential benefits from nature enhancement initiatives in the pilots can be estimated and compared to the IR estimates.
- The identification and definition of actions with each of the sectoral activities is important as this is the level at which multi-use operates. Depending on the phase of the platform development and multi-use configuration (e.g., which sectoral activities are included) different combinations of actions apply and, in turn, different reductions in cumulative impact may be obtained.
- Considerable reductions in IR can be achieved through multi-use compared to single-use. Highest reductions of approximately 40% for fish and mammals in the installation phase of the Belgian and Dutch pilots, approximately 15% for fish and mammals in the operation phase of the Dutch pilot and approximately 20% for seabed habitats in the decommissioning phase of the Belgian pilot. Note that these values do not express % IR but the relative reductions in IR from MU compared to SU.

Adapting the CIA to small-scale scenarios proved complex because the tool was originally designed to assess impacts at a sea-basin level. While great advancements have been made, not all impacts could be accounted for and some wider consequences of multi-use were described in the second part of this report, based on literature review and expert knowledge. The wider expected positive consequences of ocean multi-use projects on the marine environment are:

- Strong possibility to incorporate habitat restoration (specifically biogenic reefs in the North Sea) in OWF-LTA multi-use combinations.
- Biodiversity increase thanks to strong fisheries exclusions and artificial reef effect in the multi-use area, although not equivalent to a natural reef.
- A potential increase in commercial fish species if the project is well designed and well protected.
- Increased nutrient cycling and carbon sequestration in the case of multi-use including LTA.
- Sustainable food production and increased social acceptability towards offshore wind production and aquaculture.
- More space for conservation and reduction of conflicts over space use at sea.

Within the current context, technological and regulatory challenges limit the extent to which actions from different activities can be combined and the previously mentioned results take these limits into account. However, these limits may be removed in the future, thanks to technological development, but also the making of new insurances, permits and business models to promote MU projects. The CIA was applied to a potential optimal scenario and allows to explore how (further) advancements in multi-use in terms of reduction of environmental impacts can be achieved by alleviating existing impediments, e.g., from safety regulations, insurance policies and/or permit conditions. This predictive analysis indicates that MU projects could provide substantial impact risk reduction (potentially a factor 2 improvement) in a future that enables them fully.

In addition, optimization measures were identified to promote environmental benefits identified from the wider consequences of MU projects. These measures specifically target means to render OWF and aquaculture more suitable for multi-use, and to enhance positive impact on the marine environment. These measures are nature-inclusive design of infrastructures at sea, rethinking OWF decommissioning, using an electrical fleet to operate at sea and using biodegradable materials in aquaculture farms.

## 5. LITERATURE

Bergström, L., Sundqvist, F., & Bergström, U. (2013). Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Marine Ecology Progress Series*, 485, 199–210. <https://doi.org/10.3354/meps10344>

Martina Bocci, Emiliano Ramieri (coordinators) et al. (2017). Case study implementation, MUSES project. Edinburgh. <https://sites.dundee.ac.uk/muses/wp-content/uploads/sites/70/2018/02/1-Case-Study-Implementation-Introduction.pdf>

Bohnsack, J. A., & Sutherland, D. L. (1985). ARTIFICIAL REEF RESEARCH: A REVIEW WITH RECOMMENDATIONS FOR FUTURE PRIORITIES. *BULLETIN OF MARINE SCIENCE*, 37.

Bray, L., Kassis, D., and Hall-Spencer, J. M. (2017). Assessing larval connectivity for marine spatial planning in the Adriatic. *Marine Environmental Research*, 125, 73–81. <https://doi.org/10.1016/j.marenvres.2017.01.006>

Bridger Danielle, Martin J. Attrill, Bede F. R. Davies, Luke A. Holmes, Amy Cartwright, Siân E. Rees, Lucia Mascorda Cabre, Emma V. Sheehan (2022) The restoration potential of offshore mussel farming on degraded seabed habitat. *Aquaculture, Fish and Fisheries*, 2, 437–449. <https://doi.org/10.1002/aff2.77>.

Carey, D., Wilber, D., Read, L., Guarinello, M., Griffin, M., & Sabo, S. (2020). Effects of the Block Island Wind Farm on Coastal Resources: Lessons Learned. *Oceanography*, 33(4), 70–81. <https://doi.org/10.5670/oceanog.2020.407>

Campbell D. (2017). Albatern WaveNet Device Isle of Much Deployment. <http://grebeproject.eu/wp-content/uploads/2017/09/Wave-Energy-Albatern-WaveNet-Scotland.pdf>

Coates, D. A., Kapasakali, D.-A., Vincx, M., & Vanaverbeke, J. (2016). Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea. *Fisheries Research*, 179, 131–138. <https://doi.org/10.1016/j.fishres.2016.02.019>

Coolen, J. W. P., Van Der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G. W. N. M., Faasse, M. A., Bos, O. G., Degraer, S., & Lindeboom, H. J. (2020). Benthic biodiversity on old platforms, young wind farms, and rocky reefs. *ICES Journal of Marine Science*, 77(3), 1250–1265. <https://doi.org/10.1093/icesjms/fsy092>

Culhane, F. E., Frid C. L. J., Royo Gelabert, E., White, L., Robinson, L. A.. (2018). Linking marine ecosystems with the services they supply: what are the relevant supporting units? *Ecological applications*, 28 (7), 1740-1751. <https://esajournals.onlinelibrary.wiley.com/doi/10.1002/eap.1779>

Dannheim, J., Bergström, L., Birchenough, S. N. R., Brzana, R., Boon, A. R., Coolen, J. W. P., Dauvin, J.-C., De Mesel, I., Derweduwen, J., Gill, A. B., Hutchison, Z. L., Jackson, A. C., Janas, U., Martin, G., Raoux, A., Reubens, J., Rostin, L., Vanaverbeke, J., Wilding, T. A., ... Degraer, S. (2020). Benthic effects of offshore renewables: Identification of knowledge gaps and urgently needed research. *ICES Journal of Marine Science*, 77(3), 1092–1108. <https://doi.org/10.1093/icesjms/fsz018>

De Borger, E., Ivanov, E., Capet, A., Braeckman, U., Vanaverbeke, J., Grégoire, M., & Soetaert, K. (2021). Offshore Windfarm Footprint of Sediment Organic Matter Mineralization Processes. *Frontiers in Marine Science*, 8, 632243. <https://doi.org/10.3389/fmars.2021.632243>

De Raedemaeker, F., Sandra, M., Devriese, L., Gin, I., Altvater, S., Vidal Rigo, M., Alomar, C., Deudero, S., Mata Lara, M. (2020). Learning Lab report North Sea. D3.4 Aqua-Lit project, 72 pp. Flanders Marine Institute (VLIZ), Oostende. <http://www.vliz.be/nl/imis?module=ref&refid=328675>

Det Norske Veritas (DNV. (2021). Marine Aquaculture Forecast to 2050. <https://www.dnv.com/focus-areas/offshore-aquaculture/marine-aquaculture-forecast/index.html#>.

Degraer, S., Carey, D., Coolen, J., Hutchison, Z., Kerckhof, F., Rumes, B., & Vanaverbeke, J. (2020). Offshore Wind Farm Artificial Reefs Affect Ecosystem Structure and Functioning: A Synthesis. *Oceanography*, 33(4), 48–57. <https://doi.org/10.5670/oceanog.2020.405>

---

Degraer, S., Brabant, R., Rumes, B., & Vigin, L. (2021). Environmental impacts of offshore wind farms in the Belgian part of the North Sea. *Scientific Reports Series: Memoirs on the Marine Environment*. [https://od-nature.naturalsciences.be/downloads/mumm/windfarms/winmon\\_report\\_2022\\_final.pdf](https://od-nature.naturalsciences.be/downloads/mumm/windfarms/winmon_report_2022_final.pdf)

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science*, 4. <https://doi.org/10.3389/fmars.2017.00100>

European Environment Agency. (2019). *Nutrient enrichment and eutrophication in Europe's seas: Moving towards a healthy marine environment*. Publications Office. <https://data.europa.eu/doi/10.2800/092643>

Fowler, A. M., Jørgensen, A.-M., Svendsen, J. C., Macreadie, P. I., Jones, D. O. B., Boon, A. R., Booth, D. J., Brabant, R., Callahan, E., Claisse, J. T., Dahlgren, T. G., Degraer, S., Dokken, Q. R., Gill, A. B., Johns, D. G., Leewis, R. J., Lindeboom, H. J., Linden, O., May, R., Murk, A. J., Ottersen, g., Schroeder, D. M., Shastri, S. M., Teilmann, J., Todd, V., Van Hoey, G., Vanaverbeke, J., and Coolen, J. W. P. 2018. Environmental benefits of leaving offshore infrastructure in the ocean. *Frontiers in Ecology and the Environment*, 16, 571–578. <https://doi.org/10.1002/fee.1827>

Freeman, M.C., Garavelli, L., Wilson, E., Hemer, M., Abundo, M.L., Travis, L.E. (2022). Offshore Aquaculture: a Market for Ocean Renewable Energy. Report for Ocean Energy Systems (OES).

Gill, A. B., Birchenough, S. N. R., Jones, A. R., Judd, A., Jude, S., Payo-Payo, A., and Wilson, B. (2018). Environmental implications of offshore energy. In K. L. Yates, & C. J. A. Bradshaw (Eds.), *Offshore energy and marine spatial planning* (pp. 132–168).

Gin, I., Lheureux, G., Altvater, S., De Raedemaeker, F., Devriese, L., Mata Lara, M., Sandra, M., Vidal Rigo, M., Alomar, C., Deudero, S. (2020). Learning Lab outcome. Portfolio of best practice fact sheets, 93 pp. available online at: D3.5 Aqua-Litproject, Nausica'a: Wimereux [https://aqua-lit.eu/assets/content/D3.5\\_Best\\_practice\\_factsheets\\_watermark.pdf](https://aqua-lit.eu/assets/content/D3.5_Best_practice_factsheets_watermark.pdf)

Glarou, M., Zrust, M., & Svendsen, J. C. (2020). Using Artificial-Reef Knowledge to Enhance the Ecological Function of Offshore Wind Turbine Foundations: Implications for Fish Abundance and Diversity. *Journal of Marine Science and Engineering*, 8(5), 332. <https://doi.org/10.3390/jmse8050332>

Global Ghost Gear Initiative. (2021). *Best Practice Framework for the Management of Aquaculture Gear*. Prepared by Huntington, T. of Poseidon Aquatic Resources Management Ltd. for GGGI, 81 pp.

Halouani, G., Villanueva, C.-M., Raoux, A., Dauvin, J. C., Ben Rais Lasram, F., Foucher, E., Le Loc'h, F., Safi, G., Araignous, E., Robin, J. P., & Niquil, N. (2020). A spatial food web model to investigate potential spillover effects of a fishery closure in an offshore wind farm. *Journal of Marine Systems*, 212, 103434. <https://doi.org/10.1016/j.jmarsys.2020.103434>

Hemer M., Franklin E., Hayward J., Shoushtari M.A. (2020). Energy demand analysis of Offshore Aquaculture. A report for the Blue Economy Co-operative Research Centre. 66pp.

Hipólito, C., Vale, M., Devriese, L., Paramio, L. (2020). Policy Recommendations to Tackle Aquaculture Debris. Deliverable 5.1. developed by FRCT under the AQUA-LITProject (GA. EASME/EMFF/2017/1.2.1.12/S2/04/S12.789391), Azores, 32pp.

Huntington, T. (2019). *Marine Litter and Aquaculture Gear – White Paper*. Report produced by Poseidon Aquatic Resources Management Ltd for the Aquaculture Stewardship Council, 20 pp.

Jansen, H. M., Van Den Burg, S., Bolman, B., Jak, R. G., Kamermans, P., Poelman, M., & Stuiver, M. (2016). The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. *Aquaculture International*, 24(3), 735–756. <https://doi.org/10.1007/s10499-016-9987-y>

Jones, A. R., Alleway, H. K., McAfee, D., Reis-Santos, P., Theuerkauf, S. J., & Jones, R. C. (2022). Climate-Friendly Seafood: The Potential for Emissions Reduction and Carbon Capture in Marine Aquaculture. *BioScience*, 72(2), 123–143. <https://doi.org/10.1093/biosci/biab126>

---

Krause-Jensen, D., & Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, 9(10), 737–742. <https://doi.org/10.1038/ngeo2790>

Kühn, S., Bravo Rebolledo, E.L., and Van Franeker, J.A. (2015). Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer, Berlin. [https://doi.org/10.1007/978-3-319-16510-3\\_4](https://doi.org/10.1007/978-3-319-16510-3_4)

Lengkeek, W., Didderen, K., Teunis, M., Driessen, F., Coolen, J.W.P., Bos, O.G., Vergouwen, S.A., Raaijmakers, T., de Vries, M.B., van Koningsveld, M. (2017). Eco-friendly design of scour protection: potential enhancement of ecological functioning in offshore wind farms: Towards an implementation guide and experimental set-up. Bureau Waardenburg Report 17-001.

Lukic, I., Schultz-Zehden, A., Strothotte, E., Jaeger, M., Sorensen, C. H., Drigkopoulou, I., Nevejan, N., Kerkhove, T., Hoekstra, R., Van Den Burg, S., Declercq, A., Stechele, B., Poelman, M., Stelljes, N., Iatrou S., Stavrou A (2020). Revision of the current environmental assessment and status of pilots UNITED Deliverable 4.1, 30 July 2020.

Mavraki, N., Degraer, S., Vanaverbeke, J., & Braeckman, U. (2020). Organic matter assimilation by hard substrate fauna in an offshore wind farm area: A pulse-chase study. *ICES Journal of Marine Science*, 77(7–8), 2681–2693. <https://doi.org/10.1093/icesjms/fsaa133>

Molen, J. V. D., Van Beek, J., Augustine, S., Vansteenbrugge, L., van Walraven, L., Langenberg, V., van der Veer, H. W., Hostens, K., Pitois, S., and Robbens, J. (2015). Modelling survival and connectivity of *Mnemiopsis leidyi* in the south-western North Sea and Scheldt estuaries. *Ocean Science*, 11, 405–424. <https://doi.org/10.5194/os-11-405-2015>

Molen, J. V. D., García-García, L. M., Whomersley, P., Callaway, A., Posen, P. E., & Hyder, K. (2018). Connectivity of larval stages of sedentary marine communities between hard substrates and offshore structures in the North Sea. *Scientific Reports*, 8(1), 14772. <https://doi.org/10.1038/s41598-018-32912-2>

MJR Power, (2023). <https://www.mjrpowers.com/2023/03/worlds-first-in-air-offshore-vessel-power-charging-system-completes-successful-harbour-trials/> - accessed May, 2023.

Møller S. (2019). Reduction of CO<sub>2</sub> Emissions in the Salmon Farming Industry: The Potential for Energy Efficiency Measures and Electrification. Master's Thesis, NTNU. Retrieved from <https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2624655>

Murcia Leon, J. P., Koivisto, M. J., Sørensen, P., and Magnant, P. (2021) Power fluctuations in high-installation- density offshore wind fleets, *Wind Energ. Sci.*, 6, 461–476, <https://doi.org/10.5194/wes-6-461-2021>

Nguyen, T. M. P., Do, D. T., & Nguyen, T. P. T. (2020). The impact of environmental pollution on aquaculture development: The case of Vietnam. *Management Science Letters*, 1873–1880. <https://doi.org/10.5267/j.msl.2019.12.032>

Onderz. Form. I., Onderz. Form. D., Tonk, L., & Jansen, H. (2019). *Notitie: Potentiële effecten van duurzame zeevlierproductie op de biodiversiteit in de Noordzee: ecosysteem diensten en/of ecologische effecten*. Wageningen Marine Research. <https://doi.org/10.18174/470707>

OSPAR. (1998). OSPAR Convention for the Protection of the Marine Environment of the Northeast Atlantic decision 98/3 on the Disposal of Disused Offshore Installations. Meeting of the OSPAR Commission from 22–23 July 1998.

Piet G., Grundlehner A., Jongbloed R., Tamis J., de Vries P. (submitted). SCAIRM: a Spatial Cumulative Assessment of Impact Risk for Management. *Ecological Indicators*

Price, C. S., Morris, J. A., Keane, E. P., Morin, D. M., Vaccaro, C., & Bean, D. W. W. (2017). *Protected species and marine aquaculture interactions*. <https://repository.library.noaa.gov/view/noaa/16942>

Reubens, J. T., Degraer, S., & Vincx, M. (2014). The ecology of benthopelagic fishes at offshore wind farms: A synthesis of 4 years of research. *Hydrobiologia*, 727(1), 121–136. <https://doi.org/10.1007/s10750-013-1793-1>

Ross, F. W. R., Boyd, P. W., Filbee-Dexter, K., Watanabe, K., Ortega, A., Krause-Jensen, D., Lovelock, C., Sondak, C. F. A., Bach, L. T., Duarte, C. M., Serrano, O., Beardall, J., Tarbuck, P., & Macreadie, P. I. (2023). Potential role of seaweeds in climate change mitigation. *Science of The Total Environment*, 885, 163699. <https://doi.org/10.1016/j.scitotenv.2023.163699>

Rozemeijer M.J.C., van de Wolfshaar K.E. (2019). Desktop study on autecology and productivity of European lobster (*Homarus gammarus*, L) in offshore wind farms. Wageningen Marine Research report C109/18. KB-30: Resource Use Efficiency (project no. KB-30-002-011).

Scheidat, M., Tougaard, J., Bresseur, S., Carstensen, J., Van Polanen Petel, T., Teilmann, J., & Reijnders, P. (2011). Harbour porpoises (*Phocoena phocoena*) and wind farms: A case study in the Dutch North Sea. *Environmental Research Letters*, 6(2), 025102. <https://doi.org/10.1088/1748-9326/6/2/025102>

Skirtun, M., Sandra, M., Strietman, W. J., van den Burg, S. W. K., Raedemaeker, F. D., Devriese, and L. I. (2022). Plastic pollution pathways from marine aquaculture practices and potential solutions for the North-East Atlantic region, *Marine Pollution Bulletin*, 174, 113178, <https://doi.org/10.1016/j.marpolbul.2021.113178>

Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., & Wirtz, K. W. (2019). The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. *Hydrobiologia*, 845(1), 35–53. <https://doi.org/10.1007/s10750-018-3653-5>

Stelzenmüller, V., A. Gimpel, H. Haslob, J. Letschert, J. Berkenhagen & S. Brüning (2021) Sustainable co-location solutions for offshore wind farms and fisheries need to account for socio-ecological trade-offs. *Science of The Total Environment*, 776, 145918

Syse, H. (2016). Investigating off-grid energy solutions for the salmon farming industry. Masters Thesis, University of Strathclyde. Glasgow, Scotland. Retrieved from [http://www.esru.strath.ac.uk/Documents/MSc\\_2016/Syse.pdf](http://www.esru.strath.ac.uk/Documents/MSc_2016/Syse.pdf)

Tidbury, H., Taylor, N., Molen, J., Garcia, L., Posen, P., Gill, A., Lincoln, S., Judd, A., & Hyder, K. (2020). Social network analysis as a tool for marine spatial planning: Impacts of decommissioning on connectivity in the North Sea. *Journal of Applied Ecology*, 57(3), 566–577. <https://doi.org/10.1111/1365-2664.13551>

Tonk L. & M.J.C. Rozemeijer (2022). Passive fisheries of brown crab (*Cancer pagurus*) and European lobster (*Homarus gammarus*) in Dutch offshore wind farms. With reflections on its feasibility as a form of multi-use in offshore wind farms. Wageningen Marine Research Report C050/22. DOI: <https://doi.org/10.18174/576744>

Topham, E., Gonzalez, E., McMillan, D., and João, E. 2019. Challenges of decommissioning offshore wind farms: Overview of the European experience, *Journal of Physics: Conference Series*, 1222, 012035. 10.1088/1742-6596/1222/1/012035

Van Gerven, A., Kerkhove, T.R.H., Degraer, S., Maes, F., Staufenberger, T., Lamprakopoulou, E., Lukic, I., Hoekstra, R., Declerq, A.M., Legrand, S. (2023). “Report on environmental assessment and validation”, *UNITED Deliverable 8.3*.

Visch, W., Kononets, M., Hall, P. O. J., Nylund, G. M., & Pavia, H. (2020). Environmental impact of kelp (*Saccharina latissima*) aquaculture. *Marine Pollution Bulletin*, 155, 110962. <https://doi.org/10.1016/j.marpolbul.2020.110962>

Ziegler, L., Gonzalez, E., Rubert, T., Smolka, U., Melero, and J. J. (2018). “Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 1261–1271. <https://doi.org/10.1016/j.rser.2017.09.100>

Zhang, J., Hansen, P. K., Fang, J., Wang, W., & Jiang, Z. (2009a). Assessment of the local environmental impact of intensive marine shellfish and seaweed farming—Application of the MOM system in the Sungo Bay, China. *Aquaculture*, 287(3–4), 304–310. <https://doi.org/10.1016/j.aquaculture.2008.10.008>

Zhang, J., Hansen, P. K., Fang, J., Wang, W., & Jiang, Z. (2009b). Assessment of the local environmental impact of intensive marine shellfish and seaweed farming—Application of the MOM system in the Sungo Bay, China. *Aquaculture*, 287(3–4), 304–310. <https://doi.org/10.1016/j.aquaculture.2008.10.008>

## ANNEX 1 – DESCRIPTION OF THE PILOTS

### Pilot 1: FINO3 (FUE, Germany)

#### Description:

The offshore research platform FINO3 in the North Sea is now operated by FuE-Zentrum. The basic fundament of the platform follows the same characteristics as has been constructed for the offshore wind farm turbines in the area. The experiences from its operation and the results of the numerous scientific research projects carried out so far on and at the platform have helped the wind farm operators and wind turbine manufacturers in the planning, building, and future operation of offshore wind farms. As such FINO3 is well placed to take up an offshore wind and aquaculture demonstration project and will be able to enhance the development from pilot scale to a possible commercial application.

#### Objectives:

- ▶ **The first objective** of a possible demonstration project at FINO3 is to reduce the **technological, financial, health and safety, and environmental risks** of multi stakeholder undertakings and to accelerate the acceptance of multi-use concepts by North Sea industries. To address the risks, the data management system would be developed, including expanded modus of automatization of data collection and transmission. Furthermore, the knowledge on interactions between target culture species with other natural biota and the effects of such on aquaculture farms on the offshore environment need to be investigated. Since the data for future regulations and permissions of large scale farms is scarce, the available information base must be improved to allow investors, bankers and insurance policies to fully engage in this new industry.
- ▶ **The second objective is to demonstrate the societal acceptance of such developments and its benefits.** There is a need to develop possible business models and explore local cooperative ownership opportunities while also creating a positive “climate” in the public at large particularly because offshore facilities are in need of strong support from land based stations.
- ▶ Moreover, such joint (multi-stakeholder) activity can also **benefit both development in regards to shared costs, better social/environmental image of involved businesses, and overall increased financial yield for investors.** An opportunity for certain eco label/small spatial footprint certification can also be explored, both for marketing the aquaculture products as well as for the renewable energy derived from the multi-use site.
- ▶ The demonstrator project will provide small and medium-size companies or EU institutions with an opportunity to build up reference guidelines and demonstrate their performance capability under realistic conditions.

#### Stakeholders:

- Offshore wind sector
- Aquaculture suppliers
- Commercial aquaculture producer
- Government
- Insurance companies

### Pilot 2: North Sea Innovation Lab (Den Haag, The Netherlands)

#### Description:

North Sea Innovation Lab is an independent test site for research, pilots and the upscaling of innovations in the field of seaweed cultivation, floating solar and other renewable energy innovations, and co-use of wind farms. North Sea Innovation Lab is located 12 kilometres off the coast of The Hague – Scheveningen with the following technical specifications:

- 600ha/ 6km<sup>2</sup>
- 12 km offshore (harbour Scheveningen)
- Water depth approx. 18-20m

- 
- Officially demarcated (cardinal buoys & registered in hydrographic cards)
  - Known area by stakeholders

#### Objectives:

##### **Demonstration of offshore solar integration in offshore wind farms**

- Demonstrate the economic feasibility of integrating floating solar at existing/to-be-developed offshore wind farms at power station/turbine level
- Reduce technical risks of integrating floating solar at existing/to-be-developed offshore wind turbines by means of demonstration
- Define legal and contractual framework for applying the combination in a commercial setting

##### **Demonstration of a safe operational plan for the commercial roll-out of integrated aquaculture in offshore wind farms**

- Demonstrate the economic feasibility of integrating aquaculture at existing/to-be-developed offshore wind farms
- Develop and demonstrate a safe operational plan for commercial roll-out of seaweed activities (seeding, growing, harvesting, processing) in wind farms by means of simulation and demonstration
- Define legal/contractual framework for applying the combination in a commercial setting

##### **Demonstrate and quantify the wave dampening of floating solar array**

- Demonstrate the existence and extent of the wave dampening effect of floating solar infrastructure at sea by means of a multi-scale approach (field measurements and numerical modelling)
- Define the most efficient configuration of an (up-scaled) floating solar field in relation to an aquaculture field (at NSIL location) to optimally benefit from the wave dampening effect

##### **Demonstrate Remote Monitoring**

- Demonstrate the technical feasibility of an energy and communications connection between aquaculture and floating solar power production systems
- Demonstrate the operational feasibility of using the solar power production system as an energy and communication hub for aquaculture
- Demonstrate the impact on the aquaculture business case by combining it with solar power

#### Stakeholders:

- Stichting Noordzeeboerderij/North Sea Farm Foundation: non-profit organization aimed at realizing seaweed industry in The Netherlands
- The Seaweed Company (TSC): commercial seaweed company cultivating certified seaweed at open sea
- Oceans of Energy BV (OOE): first company to design, develop and build floating solar systems that can withstand robust, offshore conditions
- Ventolines BV: service provider of onshore wind and solar and offshore wind projects
- TNO: supports with research on floating solar energy offshore.
- Vattenfall: Wind farm operator that is interested in impacts of logistics, governance and insurance in multi-use activities in offshore wind farms.
- Government.
- Search & rescue.
- Commercial shipping.
- Fishing.
- Recreation.
- Offshore wind. etc.

---

## **Pilot 3 : Integration of native flat oyster production, flat oyster restoration and seaweed cultivation in an offshore wind farm (Belgium)**

### Description:

The project is being carried out in two locations: offshore in the wind farm of Belwind, with Parkwind as concession holder. This wind farm is located at 50 km from the coast (average depth 25-30 m). Secondly, there has been a nearshore site (Westdiep) at 5 km from the coast in front of Nieuwpoort (average depth 15 m) in which the most suited systems and techniques have been assessed to be implemented offshore.

Today, 399 offshore wind turbines are operational in the Belgian part of the North Sea, with a total installed capacity of 2260 MW. The present turbines are located in eight offshore wind farms, amongst which C-Power nv ([www.c-power.be](http://www.c-power.be)) and Belwind nv (one of the farms of Parkwind ([www.parkwind.eu/en/projects](http://www.parkwind.eu/en/projects))). Within these two wind farms, an offshore mussel aquaculture pilot project Edulis had been running from September 2016 to 2019. As such, the wind farms have extensive experience with offshore longline systems and bivalve aquaculture.

### Operational challenges.

Parkwind as a 360 degrees' company develops, finances, builds and operates offshore wind farms in the North Sea since 2009. The vast experience of the Parkwind team builds on the success of the wind farms Belwind (55 wind turbines), Nobelwind (50 wind turbines) and Northwind (72 wind turbines). Parkwind today operates 552 MW in the Belgian territorial waters and will have a pipeline of 554 MW offshore in Belgium and Ireland. Its latest project is the Northwester 2 (start 2019) which will supply 219 MW (23 wind turbines).

The nearshore site of Westdiep had several longlines since April 2017, being part of the Belgian project Value@Sea and privately owned by Brevisco (partner). The lines were used for test productions of flat oysters, blue mussels and seaweed.

In this pilot, the nearshore site has been used for testing oyster growing equipment, nature-inclusive mattresses and for seaweed techniques. Only the systems that proved to work nearshore, have been implemented in the offshore pilot site of Belwind.

### Objectives:

**The primary objective of the pilot is to evaluate wind farms as location for restoring native flat oyster reefs in combination with culturing flat oysters for human consumption.**

- To identify appropriate areas for oyster reef restoration in offshore wind farms where trawling activities are not allowed.
- To demonstrate the possibility to develop scour protection that fulfils the technical requirements but at the same time supports the formation of small oyster reefs, which eventually can form a network of small islands of oysters spread over several square kilometres. Choice of filling material is a crucial parameter.
- To design a longline that supports flat oyster production in offshore conditions (based on previous experience).
- To identify appropriate seed collectors and grow-out systems for flat oysters offshore.
- To develop remote monitoring to follow-up oyster growth in function of the environmental parameters.
- To optimize the communication and time schedules between the different activities in order to improve the efficiency of installation and data collection.
- To identify the synergy between oyster reef restoration, aquaculture and the production of

---

wind energy.

**The secondary objective of the pilot is to compare the growth of seaweed grown offshore and nearshore**

For that purpose the longlines that hold the oysters, will be used to attach seeded ropes with different seaweed species. Morphological and nutritional characteristics are known to be influenced by the dynamics of the environment and may offer opportunities to culture seaweed for specific purposes.

**Stakeholders:**

- 4SEA (4 environmental NGOs: WWF, Natuurpunt, Greenpeace, Bond Beter Leefmilieu)
- Fishery sector (including fish auction)
- Port authorities
- Regional and local authorities
- Local recreational companies, e.g. sailing clubs.

## **Pilot 4: Tourism at Middelgrunden Wind (Denmark)**

**Description:**

The pilot in Denmark considers multi-use of tourism and offshore wind farms (OWF) that result from shared sea space, joint on and offshore infrastructure and operational activities. These include OWF sightseeing boat tours and shared onshore facilities such as OWF related information centres and museums. The cooperative owned OWF Middelgrunden Wind outside the harbour of Copenhagen is sporadically used for visits by students from abroad, companies and other people interested in offshore wind. Every two years the cooperative have an open house for the share owners consisting of a boat trip and climbing the wind turbine.

**Objectives:**

- ▶ This pilot is expected to increase the TRL level (Level 7 or higher) of the multi-use solution and to expand tourism activities related to OWF (boat tours, leisure fishing and diving) in such a way that it can be a part of the general tourism offer in Copenhagen and the region.
- ▶ The pilot is to serve as a demonstrator of the improved multi-use information technology (boat scheduling system) and physical technology (facilities for divers on the platform) and advise the H&S practices, regulation - safety zone measures, and demonstrate operability and profitability of the multi-use solution.
- ▶ **Synergies that can be potentially established between OWF and tourism at the site include:**
  - Sightseeing boat tours combined with angling
  - Specially designed platforms around the turbines serving as designated facilities for divers, local artisanal fishers and offshore restaurants in the vicinity of OWF;
  - Boat tour operators can be engaged in OWF related monitoring activities;
  - On land visits to OWF information centres and museums, and platforms for observing
  - The farms with telescopes from the Round Tower Museum;
  - Helicopter flights around OWF or use of VR (virtual reality) goggles to simulate the flight around the turbines or the VR 360 view from the nacelle which can be used when the weather conditions do not allow for climbing up;
  - Educational tours can increase local knowledge about the importance of green energy.

**Additional objectives to be considered:**

- Support the development of viable business models and capacity building for local tourism operators
- Mainstream such solutions in local development policies, cohesion policies, and as part of broader project development guidance for OWF developers (esp. with regards to consultation and mitigation processes).
- Explore transferability of such multi-use solution to other regions/Member States. Where in the EU is this multi-use relevant – transferability of Danish pilot to which countries/OWF. This Danish pilot will develop general business models from existing examples to support financial viability of future

---

developments in other areas. Such model will include guidance for cost-benefit analysis.

#### **Stakeholders:**

- **Engagement of local intermediaries and clusters such as tourist boards and local councils** will be crucial as these can have a strong role in initiating and supporting the long-term functioning of this multi-use, mainly by identifying opportunities, facilitating cooperation and promoting MUCL concepts.
- **Boat and diving tour operators** - one of the aims of this pilot is to empower the sector by gathering relevant tourism stakeholders and maintaining a network of local tour operators.
- **Angling and diving associations.**
- **Local museums, exhibition and information centres.**
- **Other intermediaries incl. State of Green.**
- **Organizing visits for professionals.**

## **Pilot 5: Aquaculture/Tourism (Greece)**

#### **Description:**

KASTELORIZO AQUACULTURE SA operates a fish-farming unit, on floating facilities in the marine area near islet "Patroklos" (the islet is located near the coast, 850 meters away). The aquaculture total annual production of marine Mediterranean fish in that area is 230 tones. There is great touristic interest in the area, as many tourists visit the coasts of Patroklos islet mostly with private boats on the summer. The seabed is also of great touristic value, as the area has many attractions such as an underwater stolen cars cemetery close to the mainland coast. Another significant attraction are the many shipwrecks that have taken place in that area as well as ancient artefacts, making Scuba-diving activities quite popular in that area.

#### **Objectives:**

Based on existing activities of the aquaculture and tourism sector in the shared marine space, prospective activities and functions are described below:

- Applied technologies to establish more effective production in terms of aquaculture (monitoring parameters such as salinity, water quality, fish behaviour and stress levels);
- Monitoring and management technologies to facilitate the need for synchronization of multiple operations of touristic diving boats and recreational activities with operational vessels to the aquaculture site;
- Support in management and planning decisions for new developments, such as extension of the aquaculture unit, in order not to intervene to current touristic activities;
- Business development and minimizing costs by combining activities from both sectors. Scenarios for these combined activities could be a) diving expeditions to the aquaculture units as a new recreational attraction for divers, b) diving expeditions and use of special equipment (ROVs) from the diving centre to facilitate aquaculture operational activities in cases of emergency or for risky procedures
- Time management by multi-sharing of infrastructure such as use of existing platform for aquaculture, diving or third party vessels
- Monitoring parameters such as water quality to timely track any pollution threat to marine area;
- To facilitate touristic growth of the area in combination with social acceptance of the aquaculture activities already taking place in the area, these prospective activities could take place.

#### **Expected impacts:**

- Aquaculture unit will gain acceptance and continue developing and producing better quality food;
- Important touristic attractions in place that are merely exploited today, will now contribute to growth of the wider area and to local business expansion;
- Trained and certified offshore staff with permissions and insurance in place;
- Benefit from exploiting same marine space;



- 
- Co-use of transportation;
  - Co-use of offshore experience.

**Stakeholders:**

- Kastelorizo SA Aquaculture.
- Planet Blue diving center.
- Local ministry office.
- Local community.
- Tourists – scuba-divers.
- Local chamber of commerce or offices of tourism.

## ANNEX 2 – ACTIONS CONSIDERED IN THE UNITED PI-LOTS

<i>Definitions of the actions as used in the report</i>	
Actions	Description
Accommodation of people	Presence and influence of accommodation for people. (So NOT the actions of humans. Think on presence of structure, light, noise.
Aerial structures	Retrieval and replacement of structures above the water column for maintenance: think on wind turbines, includes moving parts.
	The partial or complete removal of structures above the water column : think on wind turbines, includes moving parts.
	Think about wind turbines, includes moving parts.
Benthic hard substrates	Installing any form of hard substrate on the seabed: think on restoration systems, anchors. Small scale approach
	Retrieval and replacement of benthic hard substrates for maintenance or harvesting. Think on cultivation systems, anchors. Small scale approach.
	The partial or complete removal of benthic hard substrates. Think on cultivation systems, anchors, scour protection, etc.
	The continued presence of hard substrates. Think on cultivation systems, anchors, scour protection.
Diving	Tourism, research or monitoring activities that includes freediving, scuba diving and ROV operations.
Dredging and disposal	Large-scale removal of seabed substrates and disposal.
Electric and telecommunication cables in the seafloor	Laying cables for e.g. electricity or communications. NB: part of the installation, not the operations.
	Retrieval and replacement of (electric or telecommunication) cables in the seafloor for maintenance and adaptation
	The partial or complete removal of (electric and telecommunication) cables in the seafloor.
	Active electric or telecommunication cables in the seafloor.
	Retrieval and replacement of (electric and telecommunication) cables in the water column.
	Laying cables for e.g. electricity or communications. NB: it is on the installation, not the operations.

Floating structures	Installing any form of substrate floating on sea surface: think on solar panel systems, buoys etc.
	Retrieval and replacement of any form of floating structures on the sea surface for maintenance: think on solar panel systems, buoys.
	The partial or complete removal of floating structures on the sea surface: think on solar panel systems, buoys, etc.
	The continued presence of floating structures on the sea surface: think on solar panel systems or buoys.
Fouling removal	Removal of fouling fauna with subsequent release at site.
	Removal of fouling fauna with subsequent release at site.
Foundation and installations	Installation of heavy components with large industrial equipment and facilities: e.g. monopile drilling, large fixed anchoring structures, installation of rotors, blades
	Partial or permanent removal of heavy components with large industrial approach equipment: e.g. anti-scouring, large fixed anchoring structures, rotors, blades
Hard substrates in the water column	Retrieval and replacement of hard structure in the water column for maintenance: e.g. cultivation basket, monopiles
Lines or nets in the water column	Retrieval and replacement of lines or nets in the water column for harvesting or maintenance: e.g. harvesting sea weed, repairing fish cages.
	The continued presence of lines or nets in water the column: e.g. nets for seaweed, hang culture mussels, fish.
	The partial or complete removal of lines or nets in the water column: e.g. seaweed lines, fish cages, etc.
	Think on deployment buoys and mooring and lines and nets of hang cultures of oysters, mussels and seaweed.
Manual labour	Presence, movements and actions of humans moving around on the activities (so NOT activities on board of a vessel). E.g. taking care of the species of interest by providing what is needed for survival or repairs on platform.
Monitoring of the environment	Monitoring of environmental criteria to track their development in time and space.
Monitoring of the targets	Monitoring of the activity if the predefined targets are met.
Pelagic structures	Installing any form of hard structure suspended in the water column or rises from the seabed.
	The partial or complete removal of hard structure in the water column. Includes parts of oyster cultivation system as baskets
	The continued presence of hard structure in the water column as cultivation basket, monopiles, etc.

Pre-installation actions	A lump term for all kind of actions pre-installing, think on seismic research, seabed adaptation, etc.
Seabed restoration	Bringing the seabed in its original (pre-activity) state by e.g. removing build-up sediment or shells, filling in pits, etc. (note that the 'restoration' of the seabed to its initial state might have more negative impacts than leaving some structures, etc. in place)
Shipping	Presence and movement of ships and vessels for all purposes (including presence, movements and actions of humans moving around on board).
Species culturing	Introduction of species of interest in either seeding amounts or large amounts
	Presence and growth of the species in large numbers in a designated area.
System operation	Operation modus of the system, with associated noise, light, sunlight reflections, vibrations, moving parts, etc.

*Actions defined to specify the activities within the CIA (1 = action is part of the activity; 0 = action is not part of the activity)*

Action	Wind farms	Macro-algae	Shellfish	Finfish	Oyster reefs	Diving	Day trips	Touristic fishing	Solar platforms	Export cable
Installation										
Aerial structures	1	0	0	0	0	0	0	0	0	0
Benthic hard substrates	1	1	1	1	1	0	0	0	1	0
Dredging and disposal	1	0	0	0	0	0	0	0	0	0
Electric and telecommunication cables in the seafloor	1	0	0	1	0	0	0	0	1	1
Installation of electric cables in the water column	0	0	0	0	0	0	0	0	1	0
Floating structures	0	1	1	1	0	0	0	0	1	0
Foundation and installations	1	0	0	1	0	0	0	0	1	0
Lines or nets in the water column	0	1	1	1	0	0	0	0	1	0
Manual labour	1	1	1	0	1	0	0	0	1	0
Pelagic structures	1	1	1	1	0	0	0	0	1	0
Pre-installation actions	1	1	1	1	1	0	0	0	1	0
Shipping	1	1	1	1	1	1	0	0	1	0
Species culturing	0	1	1	1	1	0	0	0	0	0
Operational										
Accommodation of people	1	1	1	0	0	0	0	0	0	0
Aerial structures	1	0	0	0	0	0	0	0	0	0
Benthic hard substrates	1	1	1	1	1	0	0	0	1	0

*Actions defined to specify the activities within the CIA (1 = action is part of the activity; 0 = action is not part of the activity)*

Action	Wind farms	Macro-algae	Shellfish	Finfish	Oyster reefs	Diving	Day trips	Touristic fishing	Solar platforms	Export cable
Diving	1	1	1	1	1	1	0	0	1	0
Electric and telecommunication cables in the seafloor	1	0	0	1	0	0	0	0	1	1
Electric and telecommunication cables in the water column.	1	0	0	0	0	0	0	0	1	1
Floating structures	0	1	1	1	0	0	0	0	1	0
Fouling removal	1	1	1	1	0	0	0	0	0	0
Hard substrates in the water column	1	1	1	0	0	0	0	0	0	0
System operation	1	0	0	1	0	0	0	0	1	0
Lines or nets in the water column	0	1	1	1	0	0	0	1	1	0
Manual labour	1	1	1	1	1	0	1	0	0	0
Monitoring of the environment	1	1	1	1	1	0	0	0	1	0
Monitoring of the targets	1	1	1	1	0	0	0	0	1	0
Pelagic structures	1	0	1	1	0	0	0	0	0	0
Shipping	1	1	1	1	1	1	1	1	0	0
Species culturing	0	1	1	1	1	0	0	0	0	0
Decommissioning										
Aerial structures	1	0	0	0	0	0	0	0	0	0
Benthic hard substrates	1	1	1	1	1	0	0	0	1	0
Electric and telecommunication cables in the seafloor	1	0	0	1	0	0	0	0	1	1
Floating structures	0	1	1	1	0	0	0	0	1	0
Fouling removal	1	1	1	1	1	0	0	0	1	0
Foundation and installations	1	0	0	0	0	0	0	0	0	0
Lines or nets in the water column	0	1	1	0	0	0	0	0	1	0
Manual labour	1	1	1	0	1	0	0	0	1	0
Pelagic structures	1	1	1	1	1	0	0	0	1	0
Seabed restoration	1	1	1	1	1	0	0	0	1	0
Shipping	1	1	1	1	1	0	0	0	1	0

## ANNEX 3 – REPORTED DURATIONS PER PILOT

Reported durations for the pilot in the Netherlands. Duration reported per action and activity combinations in Single Use (left) and expected reduction (%) in Multi Use (right)

Action	Single Use duration (days/year)				Multi Use reduction (%)			
	Wind farms	Macro-algae	Solar platforms	Export cables	Wind farms	Macro-algae	Solar platforms	Export cables
<b>Installation</b>								
Aerial structures - alterations	55				0			
Benthic hard substrates - alterations	55	13	93		0	12	12	
Dredging and disposal	55				0			
Electric and telecommunication cables in the seafloor - alterations	96		48	92	0		50	50
Electric and telecommunication cables in the water column - alterations			20				0	
Floating structures - alterations		1	61			100	100	
Foundation and installations	0		0		0		0	
Lines or nets in the water column - alterations		8	270			7	0.6	
Manual labour	0	0	60		0	0	0	
Pelagic structures - alterations	55	0	0		0	0	0	
Pre-installation actions	83	43	40		50	5	5	
Shipping	0	0	0		0	0	0	
Species culturing - set up		0				0		
<b>Operation</b>								
Accommodation of people	365	0			0			
Aerial structures - operation	365				0			
Benthic hard substrates - presence	365	365	365		0	0	0	
Benthic hard substrates - alterations	0	0			0	0		
Diving	20	0	5		7.5	0	30	
Electric and telecommunication cables in the seafloor - presence	365		365	365	50		50	50
Aerial structures - maintenance	365				0			
Electric and telecommunication cables in the seafloor - alterations	10		10	10			0	0
Electric and telecommunication cables in the water column - alterations			365				0	
Floating structures - presence		0	365			100	0	
Floating structures - alterations		1	0			100	0	
Fouling removal	0	5			0	0		

Hard substrates in the water column	0	0			0	0		
System operation	365		365		0		0	
Lines or nets in the water column - presence		210	365				0	
Lines or nets in the water column - alterations		10	16				0	
Manual labour	365	0	0				0	
Monitoring of the environment	10	10	10		33	33	33	
Monitoring of the targets	0	0	0		0	0	0	
Pelagic structures - presence	365				0			
Shipping	0	0			0	0		
Species culturing - growing		210				0		
<b>Decommissioning</b>								
Aerial structures - alterations	55				0			
Benthic hard substrates - alterations	55	13	93		0	12	2	
Electric and telecommunication cables in the seafloor - alterations	0		0	0	0		0	0
Floating structures - alterations		1	127			100	1	
Fouling removal	0	0	0		0	0	0	
Foundation and installations	0				0			
Lines or nets in the water column - alterations		8	0			19	12	
Manual labour	0	0	0		0	0	0	
Pelagic structures - alterations	55	0	0		0	0	0	
Seabed restoration	0	0	0		0	0	0	
Shipping	0	0	0		0	0	0	

Reported durations for the pilot in Belgium. Duration reported per action and activity combinations in Single Use (left) and expected reduction (%) in Multi Use (right)

Action	Single Use duration (days/year)					Multi Use reduction (%)				
	Wind farms	Macro-algae	Shell fish	Oyster reefs	Export cables	Wind farms	Macro-algae	Shell fish	Oyster reefs	Export cables
<b>Installation</b>										
Aerial structures - alterations	55					0				
Benthic hard substrates - alterations	55	13	13	55		50	12	12	50	
Dredging and disposal	55				55	50			50	0
Electric and telecommunication cables in the seafloor - alterations	96				104	0				0

Electric and telecommunication cables in the water column - alterations										
Floating structures - alterations		1	1				100	100		
Foundation and installations	0					0				
Lines or nets in the water column - alterations		8	13				7	7		
Manual labour	0	0	0	0		0	0	0	0	
Pelagic structures - alterations	55	0	0			0	0	0		
Pre-installation actions	83	43	43	83		50	11.5	11.5	50	
Shipping	0	0	0	0		0	0	0	0	
Species culturing - set up		6	60	0			0	0	0	
<b>Operation</b>										
Accommodation of people	365	0	270			0		0		
Aerial structures - operation	365					0				
Benthic hard substrates - presence	365	365	365	365		50	0	0	50	
Benthic hard substrates - alterations	0	0	0	0		0	0	0	0	
Diving	20	0	0	20		50	0	0	50	
Electric and telecommunication cables in the seafloor - presence	365				365	0				0
Aerial structures - maintenance	365					0				
Electric and telecommunication cables in the seafloor - alterations	10				10	0				0
Electric and telecommunication cables in the water column - alterations										
Floating structures - presence		0	0				0	0		
Floating structures - alterations		1	1				0	0		
Fouling removal	0	5	0			0	0	0		
Hard substrates in the water column	0	0	40			0	0	0	0	
System operation	365					0				
Lines or nets in the water column - presence		210	365				0	0		
Lines or nets in the water column - alterations		10	0				0	0		
Manual labour	365	0	0	0		0	0	0	0	
Monitoring of the environment	10	10	10	10		25	25	25	25	
Monitoring of the targets	0	0	0			0	0	0		
Pelagic structures - presence	365		365			0		0		
Shipping	0	0	0	0		0	0	0	0	
Species culturing - growing		210	365	365			0	0	0	
<b>Decommissioning</b>										

Aerial structures - alterations	55					0				
Benthic hard substrates - alterations	55	13	13	55		50	12	12	50	
Electric and telecommunication cables in the seafloor - alterations	0				0	0				0
Floating structures - alterations		1	1				0	0		
Fouling removal	0	0	0	0		0	0	0	0	
Foundation and installations	0					0				
Lines or nets in the water column - alterations		8	13				19	12		
Manual labour	0	0	0	0		0	0	0	0	
Pelagic structures - alterations	55	0	0	0		0	0	0	0	
Seabed restoration	0	0	2	0		0	0	0	0	
Shipping	0	0	0	0		0	0	0	0	

Reported durations for the pilot in Germany. Duration reported per action and activity combinations in Single Use (left) and expected reduction (%) in Multi Use (right)

Action	Single Use duration (days/year)				Multi Use reduction (%)			
	Wind farms	Macro-algae	Shell-fish	Ex-port cables	Wind farms	Macro-algae	Shell-fish	Ex-port cables
<b>Installation</b>								
Aerial structures - alterations	55				0			
Benthic hard substrates - alterations	55	13	13		0	12	12	
Dredging and disposal	55			55	0			0
Electric and telecommunication cables in the seafloor - alterations	96			104	0			0
Electric and telecommunication cables in the water column - alterations								
Floating structures - alterations		1	1			100	100	
Foundation and installations	0				0			
Lines or nets in the water column - alterations		8	13			7	7	
Manual labour	0	0	0		0	0	0	
Pelagic structures - alterations	55	0	0		0	0	0	
Pre-installation actions	83	43	43		0	11.5	11.5	
Shipping	0	0	0		0	0	0	
Species culturing - set up		6	60			0	0	
<b>Operation</b>								
Accommodation of people	365	0	270		0		0	

Aerial structures - operation	365				0			
Benthic hard substrates - presence	365	365	365			0	0	
Benthic hard substrates - alterations	0	0	0		0	0	0	
Diving	20	0	0		0	0	0	
Electric and telecommunication cables in the seafloor - presence	365			365	0			0
Aerial structures - maintenance	365				0			
Electric and telecommunication cables in the seafloor - alterations	10			10	0			0
Electric and telecommunication cables in the water column - alterations								
Floating structures - presence		0	0			0	0	
Floating structures - alterations		1	1			0	0	
Fouling removal	0	5	0		0	0	0	
Hard substrates in the water column	0	0	40		0	0	0	
System operation	365				0			
Lines or nets in the water column - presence		210	365			0	0	
Lines or nets in the water column - alterations		10	0			0	0	
Manual labour	365	0	0		0	0	0	
Monitoring of the environment	10	10	10		33	33	33	
Monitoring of the targets	0	0	0		0	0	0	
Pelagic structures - presence	365		365		0		0	
Shipping	0	0	0		0	0	0	
Species culturing - growing		210	365			0	0	
<b>Decommissioning</b>								
Aerial structures - alterations	55				0			
Benthic hard substrates - alterations	55	13	13		0	12	12	
Electric and telecommunication cables in the seafloor - alterations	0			0	0			0
Floating structures - alterations		1	1			0	0	
Fouling removal	0	0	0		0	0	0	
Foundation and installations	0				0			
Lines or nets in the water column - alterations		8	13			19	12	
Manual labour	0	0	0		0	0	0	
Pelagic structures - alterations	55	0	0		0	0	0	
Seabed restoration	0	0	2		0	0	0	
Shipping	0	0	0		0	0	0	

Reported durations for the pilot in Denmark. Duration reported per action and activity combinations in Single Use (left) and expected reduction (%) in Multi Use (right)

Action	Single Use duration (days/year)					Multi Use reduction (%)				
	Wind farms	Diving	Day trips	Touristic fishing	Export cables	Wind farms	Diving	Day trips	Touristic fishing	Export cables
<b>Installation</b>										
Aerial structures - alterations	70					0				
Benthic hard substrates - alterations	60					0				
Dredging and disposal	60					0				
Electric and telecommunication cables in the seafloor - alterations	5				14	0				0
Electric and telecommunication cables in the water column - alterations										
Floating structures - alterations										
Foundation and installations	21					0				
Lines or nets in the water column - alterations										
Manual labour	0					0				
Pelagic structures - alterations	0					0				
Pre-installation actions	14					0				
Shipping	2	1				25	50			
Species culturing - set up										
<b>Operation</b>										
Accommodation of people	0					0				
Aerial structures - operation	365					0				
Benthic hard substrates - presence	35					0				
Benthic hard substrates - alterations	0.5					0				
Diving	0	15				0	0			
Electric and telecommunication cables in the seafloor - presence	365				365	0				0
Aerial structures - maintenance	0					0				
Electric and telecommunication cables in the seafloor - alterations	0				0	0				0
Electric and telecommunication cables in the water column - alterations	0				0	0				0
Floating structures - presence										
Floating structures - alterations										
Fouling removal	0					0				
Hard substrates in the water column	0					0				

System operation										
Lines or nets in the water column - presence				150					0	
Lines or nets in the water column - alterations	0		50	150		0		0	0	
Manual labour	0.2					0				
Monitoring of the environment	0					0				
Monitoring of the targets	365					0				
Pelagic structures - presence	60					0				
Shipping		50	50	150			0	0	0	
Species culturing - growing	365					0				
<b>Decommissioning</b>										
Aerial structures - alterations	40					0				
Benthic hard substrates - alterations	50					0				
Electric and telecommunication cables in the seafloor - alterations	0				0	0				0
Floating structures - alterations										
Fouling removal	0					0				
Foundation and installations	0					0				
Lines or nets in the water column - alterations										
Manual labour	0					0				
Pelagic structures - alterations	0					0				
Seabed restoration	0					0				
Shipping	0					0				

Reported durations for the pilot in Greece. Duration reported per action and activity combinations in Single Use (left) and expected reduction (%) in Multi Use (right)

Action	Single Use duration (days/year)		Multi Use reduction (%)	
	Finfish	Diving	Finfish	Diving
<b>Installation</b>				
Aerial structures - alterations				
Benthic hard substrates - alterations	2		0	
Dredging and disposal				
Electric and telecommunication cables in the seafloor - alterations	1		0	
Electric and telecommunication cables in the water column - alterations				
Floating structures - alterations	7		0	

Foundation and installations	3		0	
Lines or nets in the water column - alterations	3		0	
Manual labour				
Pelagic structures - alterations	0		0	
Pre-installation actions	10		0	
Shipping	0	0	0	0
Species culturing - set up	6		0	
<b>Operation</b>				
Accommodation of people				
Aerial structures - operation				
Benthic hard substrates - presence	365			
Benthic hard substrates - alterations	0.1		0	
Diving	182.5	196	17	0
Electric and telecommunication cables in the seafloor - presence	365		0	
Aerial structures - maintenance				
Electric and telecommunication cables in the seafloor - alterations	1		0	
Electric and telecommunication cables in the water column - alterations	0		0	
Floating structures - presence	365		0	
Floating structures - alterations	1.5		0	
Fouling removal	0		0	
Hard substrates in the water column				
System operation	0		0	
Lines or nets in the water column - presence	365		0	
Lines or nets in the water column - alterations	73		0	
Manual labour	365		0	
Monitoring of the environment	365		0	
Monitoring of the targets	0		0	
Pelagic structures - presence	365	0	0	0
Shipping	365	196	0	20
Species culturing - growing	365		0	
<b>Decommissioning</b>				
Aerial structures - alterations				
Benthic hard substrates - alterations	2		0	
Electric and telecommunication cables in the seafloor - alterations	2		0	



Funded by the European Union (H2020 Grant Agreement no 862915). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them



Floating structures - alterations	3		0	
Fouling removal	0		0	
Foundation and installations	2		0	
Lines or nets in the water column - alterations	2		0	
Manual labour				
Pelagic structures - alterations	0		0	
Seabed restoration	0		0	
Shipping	0		0	

## ANNEX 4 - DEFINING A POTENTIAL OPTIMAL SCENARIO

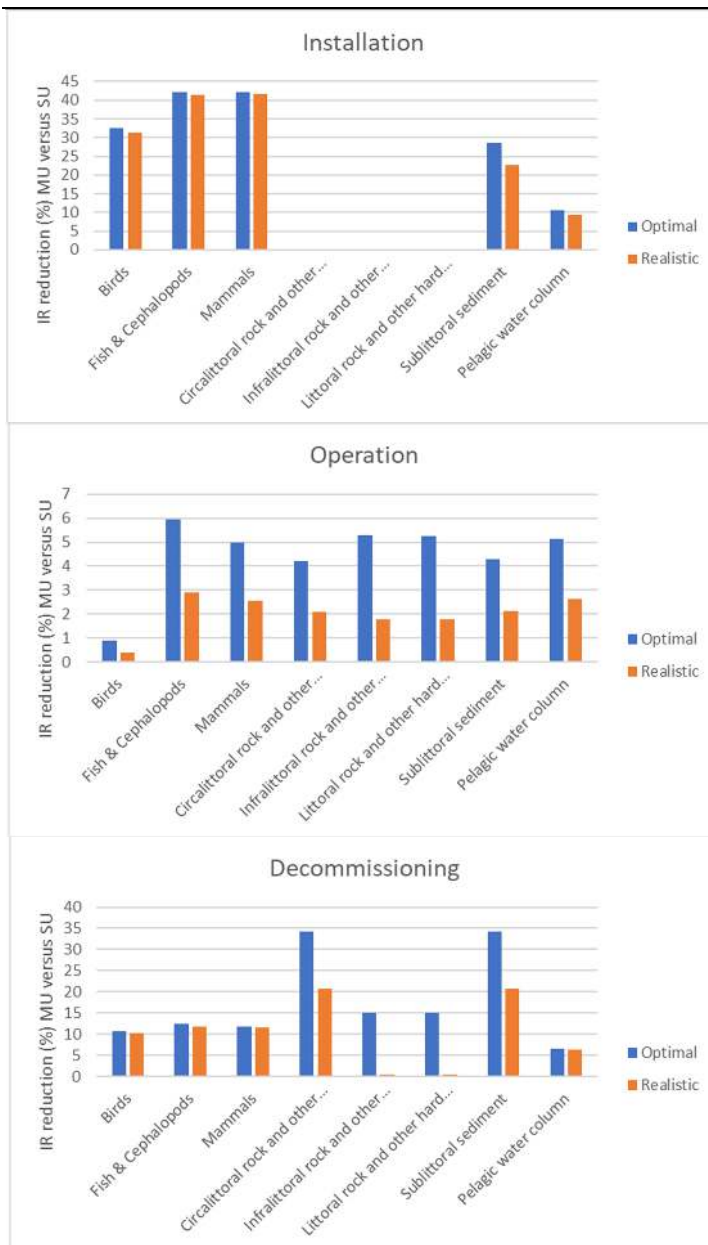
In the SU and MU pilots the cells in the actual execution of activities such as seaweed culture are defined as how they are actually performed in the Belgian pilot (Figure 6). Due to risk mitigation, only one aquaculture line is installed per cell. However, it is imaginable that the risk mitigation is explained less strictly so more aquaculture installations are allowed in a cell. In addition, newer OWFs have larger distances between higher turbines potentially having more space to install aquaculture installations close to each other. For example, sea weed aquaculture applied as an additional (Multi Use) activity together with OWFs, could in theory share infrastructure like fixed anchors with e.g. solar or other types of aquaculture.

The OWFs also have large safety zones (also known as maintenance zones) around their installations, and they have sturdy fixed structures that offer the potential of a basis for other activities

In order to investigate the potential extra reduction in IR (also as a sensitive analysis) an additional scenario was investigated with more sharing of facilities: an optimum/theoretical scenario as compared to the expected (practical/realistic, as described in the main text). In the table below, it is shown which actions have been adapted to come to a theoretical enhanced sharing form of multi-use as compared to the realistic multi-use scenarios used in the main analysis.

Action	Theoretical optimum					Realistic (used for his CIA)				
	BE	DE	DK	NL	GR	BE	DE	DK	NL	GR
<i>Installation</i>										
Aerial structures - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Benthic hard substrates - alterations	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Dredging and disposal	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Electric and telecommunication cables in the seafloor - alterations	MU	MU	MU	MU	SU	SU	SU	SU	MU	SU
Electric and telecommunication cables in the water column - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Floating structures - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Foundation and installations	SU	SU	SU	MU	SU	SU	SU	SU	SU	SU
Lines or nets in the water column - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Manual labour	MU	MU	SU	MU	SU	MU	MU	SU	MU	SU
Pelagic structures - alterations	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Pre-installation actions	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Shipping	MU	MU	MU	MU	MU	MU	MU	MU	MU	MU
Species culturing - set up	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
<i>Operation</i>										
Accommodation of people	MU	MU	SU	MU	SU	MU	MU	SU	MU	SU
Aerial structures - operation	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Benthic hard substrates - presence	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Benthic hard substrates - alterations	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Diving	MU	MU	MU	MU	MU	MU	MU	MU	MU	MU
Electric and telecommunication cables in the seafloor - presence	MU	MU	MU	MU	SU	SU	SU	SU	MU	SU
Aerial structures - maintenance	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Electric and telecommunication cables in the seafloor - alterations	MU	MU	MU	MU	SU	SU	SU	SU	MU	SU
Electric and telecommunication cables in the water column - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Floating structures - presence	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Floating structures - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Fouling removal	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU

Hard substrates in the water column	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
System operation	SU	SU	SU	MU	SU	SU	SU	SU	MU	SU
Lines or nets in the water column - presence	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Lines or nets in the water column - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Manual labour	MU	MU	MU	MU	SU	MU	MU	MU	MU	SU
Monitoring of the environment	MU	MU	SU	MU	SU	MU	MU	SU	MU	SU
Monitoring of the targets	MU	MU	SU	MU	SU	MU	MU	SU	MU	SU
Pelagic structures - presence	MU	MU	SU	SU	SU	SU	SU	SU	SU	SU
Shipping	MU	MU	MU	MU	MU	MU	MU	MU	MU	MU
Species culturing - growing	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
<i>Decommissioning</i>										
Aerial structures - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Benthic hard substrates - alterations	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Electric and telecommunication cables in the seafloor - alterations	MU	MU	MU	MU	SU	SU	SU	SU	SU	SU
Floating structures - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Fouling removal	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Foundation and installations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Lines or nets in the water column - alterations	SU	SU	SU	SU	SU	SU	SU	SU	SU	SU
Manual labour	MU	MU	SU	MU	SU	MU	MU	SU	MU	SU
Pelagic structures - alterations	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Seabed restoration	MU	MU	SU	MU	SU	SU	SU	SU	SU	SU
Shipping	MU	MU	SU	MU	SU	MU	MU	SU	MU	SU



Reduction (%) in Impact Risk for each Ecosystem Component by activities in Multi Use design as compared to Single Use design for the Belgian pilot based on the theoretical optimum scenario (blue bars) and the realistic scenario (orange bars).