North Sea Energy offshore system integration

4.1

North Sea Energy 2020-2022

Exploratory study on ecological values in relation to North Sea energy system integration

North Sea Energy 2020-2022

Unlock the low-carbon energy potential North Sea with optimal value for society and nature

The North Sea Energy program and its consortium partners aim to identify and assess opportunities for synergies between energy sectors offshore. The program aims to integrate all dominant low-carbon energy developments at the North Sea, including: offshore wind deployment, offshore hydrogen infrastructure, carbon capture, transport and storage, energy hubs, energy interconnections, energy storage and more.

Strategic sector coupling and integration of these low-carbon energy developments provides options to reduce CO2 emissions, enable & accelerate the energy transition and reduce costs. The consortium is a public private partnership consisting of a large number of (international) partners and offers new perspectives regarding the technical, environmental, ecological, safety, societal, legal, regulatory and economic feasibility for these options.

In this fourth phase of the program a particular focus has been placed on the identification of North Sea Energy Hubs where system integration projects could be materialized and advanced. This includes system integration technologies strategically connecting infrastructures and services of electricity, hydrogen, natural gas and CO2. A fit-for-purpose strategy plan per hub and short-term development plan has been developed to fast-track system integration projects, such as: offshore hydrogen production, platform electrification, CO2 transport and storage and energy storage.

The multi-disciplinary work lines and themes are further geared towards analyses on the barriers and drivers from the perspective of society, regulatory framework, standards, safety, integrity and reliability and ecology & environment. Synergies for the operation and maintenance for offshore assets in wind and oil and gas sector are identified. And a new online Atlas has been released to showcase the spatial challenges and opportunities on the North Sea. Finally, a system perspective is presented with an assessment of energy system and market dynamics of introducing offshore system integration and offshore hubs in the North Sea region. Insights from all work lines have been integrated in a Roadmap and Action Agenda for offshore system integration at the North Sea.

The last two years of research has yielded a series of 12 reports on system integration on the North Sea. These reports give new insights and perspectives from different knowledge disciplines. It highlights the dynamics, opportunities and barriers we are going to face in the future. We aim that these perspectives and insights help the offshore sectors and governments in speeding-up the transition.

We wish to thank the consortium partners, executive partners and the sounding board. Without the active involvement from all partners that provided technical or financial support, knowledge, critical feedback and positive energy this result would not have been possible.

North Sea Energy offshore system integration

4.1

North Sea Energy 2020-2022

Exploratory study on ecological values in relation to North Sea energy system integration

Prepared by:

Royal HaskoningDHV
Jens Odinga
Maren Staniek
Belinda Burtonshaw

Bureau Veritas
Pim Reuderink

TotalEnergies
Mathieu Nemec
Corstiaan Teeuwen
Tjabbo Oudkerk

Checked by:

Royal HaskoningDHV
Lucinda Rosheuvel

The project has been carried out with a subsidy from the Dutch Ministry of Economic Affairs and Climate, National Schemes EZK-subsidies, Top Sector Energy, as taken care of by RVO (Rijksdienst voor Ondernemend Nederland)

Contents

Glossary

List of abbreviations	
CCS	Carbon Capture and Storage
CVI	Close Visual Inspection
DCS	Dutch Continental Shelf (in Dutch: NCP of Nederlands Continentaal Plat)
EIA	Environmental Impact Assessment
EMF	Electro-magnetic Frequencies (or Fields)
GVI	General Visual Inspection
IRM	Inspection, Repair and Maintenance
IBTS	International Bottom Trawl Survey
MMS	Man-Made Structure(s)
MPA	Marine Protected Area
NEA	North East Atlantic
NGO	Non-Governmental Organisation
NSE	North Sea Energy
O&G	Oil and Gas
OWF	Offshore Wind Farm
OSPAR	1992 Convention for the Protection of the Marine Environment of the North-East Atlantic
P2H2	Power to Hydrogen
ROV	Remotely Operated (Underwater) Vehicle
SNS	Southern North Sea
UNCLOS	1982 Third United Nations Convention on the Law of the Sea
Wnb	Wet Natuurbescherming
WOZEP	Dutch Governmental Offshore Wind Ecological Program (Wind op Zee Ecologisch Programma)
WP	Work package

List of terms	
Energy hub	Unit of multi-carrier offshore energy systems containing energy production, conversion and/ or storage facilities.
Decommissioning	Removal from service. Here: Post-operational removal or re-use of an offshore structure.
Offshore structure	Man-made structures of offshore energy infrastructure, including oil and gas platforms, power to gas structures (P2H2), wind turbines, piles, cables and pipelines.
Rigs-to-reef	Post-operational re-use of offshore structures as artificial reefs

1 Introduction

1.1 Background

To reach net-zero carbon emissions by 2050 and thereby limit global warming to 1.5°C, a large-scale energy transition towards renewable energy solutions is crucial (IEA, 2021). In the scope of the energy transition, the North Sea offers opportunities for large-scale wind energy, hydrogen production and underground carbon storage. The North Sea Energy (NSE) programme investigates the possibilities and benefits of linking the various energy functions. By connecting and integrating the infrastructure of wind energy, hydrogen production and underground carbon storage in energy hubs[1], not only money and time can be saved, but it also leads to effective use of space and reduced carbon emissions.

The NSE research program was launched in 2017 to translate these ambitions into action. Together with over 30 private and public partners in the energy sector, the NSE program in its fourth phase conducts multi-disciplinary research including aspects like society, ecology, logistics, spatial planning and regulations and provides a roadmap for the energy transition in the North Sea. The program is funded by its partners and through public subsidies from TKI Wind op Zee and TKI New Gas.

Many initiatives in the scope of the energy transition can impact the ecology and environment in the North Sea and includes several non-energy usages of the North Sea. Local and regional ecosystems and species of the North Sea provide ecosystem services like the provision of fish stocks, carbon storage in marine sediments, and recreational values (ecosystem services: Millennium Ecosystem Assessment, 2005). In addition, the conservation (and recovery) of threatened species and habitats in the North Sea is a key concern in sustainable development and marine spatial planning (MSP).

To guide decisions in the development and planning of the North Sea and to reduce adverse ecological and environmental effects of the energy transition, a sound understanding of the marine ecosystem system is needed. As a result of varying oceanographic and ecological conditions (like bathymetry, salinity, types of sediment, availability of nutrients, effects of currents) organisms are not spread homogenously throughout the North Sea. Some specific regional drivers and barriers influence the distribution of species and define local and regional biodiversity. Over the years, a range of studies has focussed on the North Sea providing knowledge on various topics, including mapping of the North Sea. A combination of these studies can be used to identify ecologically important areas. This information can be used to support the selection of future energy hub locations in the North Sea.

Next to initiatives to connect infrastructure for future energy production, decisions must be made about existing offshore structures[2]. These structures include for example platforms built for the extraction of oil and gas and offshore windfarms, including scour protection, pipelines and cables. These decisions should be guided by potential (negative) effects on North Sea ecology as well as potential opportunities for (building with) nature.

[1] Energy hubs are defined as multi-carrier offshore energy systems consisting of production, conversion and/or storage, which are connected to the shore via (transport) corridors or interconnected internationally.

[2] In this report, “offshore structures” refer to the man-made structures of offshore energy infrastructure, including oil and gas platforms, power to gas structures (P2H2), wind turbines, piles, cables and pipelines.

As a result of the energy transition, many oil and gas platforms in the North Sea will be taken off the grid before 2050, and decommissioning strategies need to be developed for those structures. Additionally, the rapidly expanding of Offshore Wind Farms (OWFs) will create a demand for wind turbine decommissioning solutions in the future (Fowler et al., 2020). Currently, OSPAR[3], UNCLOS[4], and the IMO Guidelines for the removal of offshore installations and structures[5] provide for a general obligation to fully remove installations and structures in the North Sea at the end of their operational life. Nonetheless, exceptions can be granted for structures that will be re-used, and legislation might change as to what decommissioning scenarios are possible in the North Sea (see chapter 3.5.1 for legal feasibility).

Within the scope of the energy transition, it might be possible to re-use or repurpose existing structures. So-called “rigs-to-reef" programmes emerging around the world, where structures are re-purposed as artificial reefs have recently received considerable attention from the scientific community. For instance, the development of artificial reef sites made from old offshore infrastructure materials in the Gulf of Mexico has led to the attraction of diverse sessile species and provides crucial habitats to fish stocks (Verbeek et al., 2018).
An increasing amount of research is being conducted on potential ecological values of existing offshore structures, leading to new findings that could make it necessary to re-assess which decommissioning scenarios are ecologically favourable.

To determine whether marine species and ecosystems of the North Sea would benefit from alternative decommissioning options, ecological values on and around existing offshore infrastructures in the North Sea region need to be assessed. To this end, several research methods are available which vary in technique, cost and type of data gathered. In this report, different aspects of ecological value of offshore structures and associated methods will be discussed to support the decision-making process towards decommissioning, reuse or abandonment.

1.2 Work package contents

Within the current phase of the NSE program, work package 4 (WP4) focuses on the effects of potential developments from the energy transition on the ecology and environment (i.e., greenhouse gas emissions) in the North Sea. The work package has been divided into Ecology and Environment, where this report focuses on Ecology.

The main aim of this part of work package 4 (Ecology) is to gain a better understanding of relevant ecological information of species and ecosystems in the North Sea to support decision-making for energy hub selection and choices between decommissioning, reuse or abandonment.

To fulfil this task, we conducted two activities. First, publicly available scientific information on relevant ecological values of the North Sea was visualized by including additional map layers in the existing North Sea Energy Atlas. The NSE Atlas is a public online geographical information system that visualises different aspects of the NSE program, such as current and future offshore infrastructure and different transition opportunities. The NSE Atlas is designed to communicate about the programme to the public

[3] Convention for the Protection of the Marine Environment of the North-East Atlantic, 1992 (OSPAR)
[4] Third United Nations Convention on the Law of the Sea, 1982 (UNCLOS)
[5] IMO Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone, 1989

and to support energy companies in their decision-making process for the future energy transition and expansion. Find the latest version under: https://north-sea-energy.eu/en/energy-atlas.
Second, potential methods to estimate ecological values of existing offshore structures have been explored based on existing scientific knowledge and studies. Different types of ecological value of offshore structures have been defined and methods were compared for feasibility in the NSE context. Both these activities have been carried out by Royal HaskoningDHV. These activities are described in separate chapters in the further contents of this report.

The other part of this work package (Environment) has investigated the carbon footprint of energy hub development through a life cycle analysis (LCA) on offshore structures and their decommissioning phase. This activity has been carried out by TNO and is described in a separate report (NSE4_FinalDraft_WP4.2_LCA).

1.3 Relation to other WPs and outline

This work package aims to summarise and further develop knowledge on ecology in the North Sea in relation to the NSE program based on scientific studies and literature. This is to inform how the selection of energy hub locations and the decommissioning of existing offshore structures can potentially affect the marine ecology present in the North Sea.

As described in the introduction, the contents of work package 4 (Ecology) have been divided into two parts (or activities):

- Activity 1: Define and visualize ecological information of the North Sea
- Activity 2: Explore potential methods to estimate ecological values of existing offshore structures

The outcomes of this work package are aimed to support decisions for energy hub selections (work package 1), including their location. Hence, ecological values across different regions in the North Sea will be described where possible. In turn, hub selections from work package 1 will provide focus areas for this work package. There is also a relation to the social element within the programme (WP2), as any initiatives on the North Sea will be subject to the interests of other stakeholders and public opinion. In addition, as part of the development of energy hubs and discussing alternative decommissioning scenarios, any legal aspects (WP2) should be considered including nature permits and potential mandatory ecological assessments. Furthermore, the outcomes of this work package will provide input for the system mapping and modelling of the North Sea in WP6. And finally, work package 7 will define the roadmap for the North Sea region up to 2050 and recommendations are provided in this report for the further development of the NSE roadmap from an ecological perspective.

The outcomes of the studies in this report and phase (NSE4) are a follow-up on the results from phase 2 (NSE2) of the NSE program. In NSE2 two relevant studies were conducted. One by Royal HaskoningDHV by performing an initial assessment on the type and extent of impacts on nature (NSE2_D2_Strategic Assessment of Environmental Impacts of Offshore system Integration Options). This study examined the impacts of construction and operation of offshore energy production activities on marine ecology in the North Sea (e.g. the effects of (e.g. dredging, cables and pipelines, platform operation on primary production, benthos, fish and fish larvae, marine mammals, birds, bats through underwater noise, water quality, electro-magnetic frequencies, disturbance of habitats, amongst others). Another study was conducted by Wageningen Marine Research (WMR) (NSE2_D1_Screening impacts of offshore infrastructures on marine species groups) in which the potential cumulative effects of pressures from offshore human activities on ecology in the North Sea were screened.

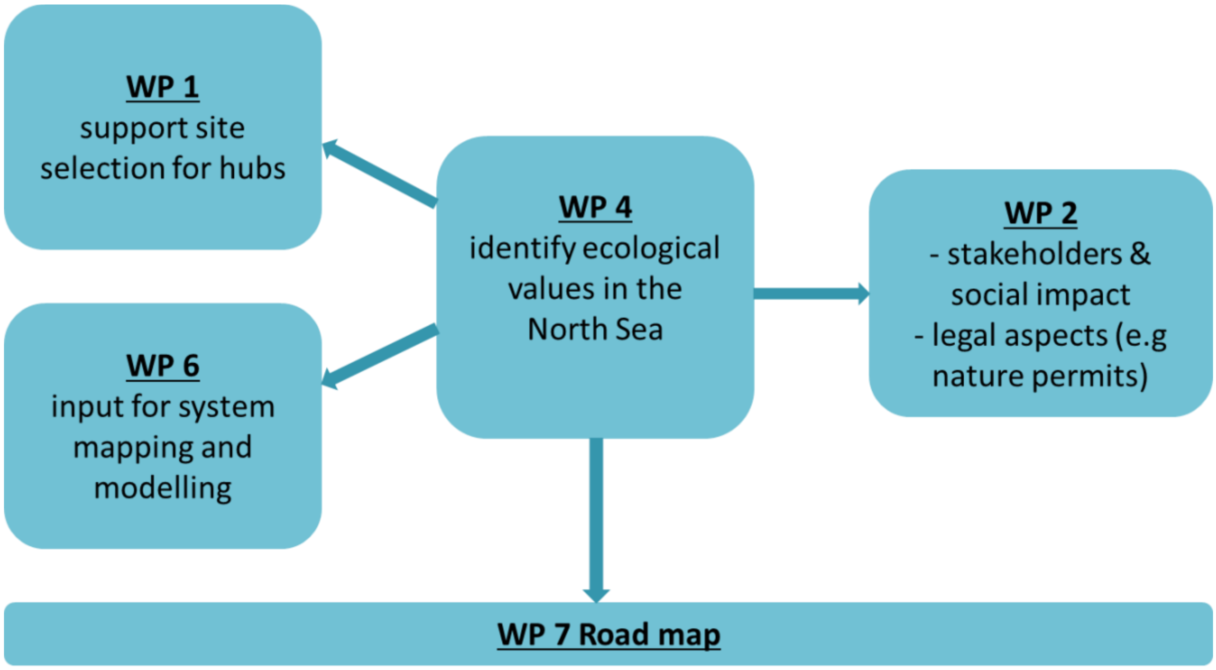

Figure 1: Relation to other NSE4 work packages

2 Visualising ecological information of the North Sea

2.1 Scope and purpose

The geographical focus of this activity is on the Dutch Continental Shelf (DCS). Where relevant and available, international data (North Sea, North East Atlantic) has been included. A temporal scale has not been applied, however, when possible and relevant, seasonal information was included, for instance with regards to the recruitment season of marine mammals. Seasonality is relevant in relation to the timing of certain activities and their effect on certain species (like underwater sound from pile driving for platforms and structures and its effect on marine mammals). Refer to the recommendations (Chapter 4) for potential future studies to further develop knowledge on this topic.

This activity has looked at recent past and present spatial datasets on species, habitats and ecosystems in the North Sea and we aimed to use the most recently available information from scientific literature. In this phase of the programme, we refrained from visualising future projections of potential ecosystem shifts related to the expansion of offshore infrastructure or related to climate change. This is due to the current lack of knowledge on future projections in relation to marine ecology, however, modelling studies are undergoing and could provide insights in the near future.

The result of this activity is a selection of map layers that visualize existing knowledge of relevant ecological information about the North Sea. These map layers have been made available to be incorporated into the NSE Atlas. Accompanying these layers, background information is given within this report on the selected layers as well as information on potential further developments of the ecological section of the NSE Atlas.

By mapping ecosystems and species of the North Sea, a first assessment of potentially ecologically important and/or vulnerable areas can be made. Identifying areas, populations and seasons especially sensitive to offshore activities and structures will support the spatial planning for future energy hubs as well as decision-making processes regarding existing offshore structures (i.e., provide supporting information in choices to abandon, re-use or decommission existing offshore structures).

Selected NGOs and research organisations have been consulted throughout the process of this activity. Key stakeholders for this activity and deliverables are platform and grid operators, policy makers and the general public, through the use of the NSE Atlas.

2.2 Research questions

To guide the aim of activity 1, the following research questions were defined:

1. Which spatial data visualizing ecological information in the North Sea is available?
2. Which ecological information is necessary to support the NSE roadmap?

2.3 Methods

2.3.1 Data gathering and inventory

To begin with, the design requirements for the map layers and relevant metadata were determined. Subsequently, a geodatabase was set up to maintain a standardized format for all imported data.

A thorough review of recent literature and publicly available databases (e.g. EMODnet, Noordzeeloket, Informatiehuis Marien and the Wageningen GeoServer) was conducted and an inventory of relevant sources was created. Relevance for inclusion was defined by the following criteria:

a. Publicly available/ published and accessible
b. Spatial scope: DCS, North Sea or North-East Atlantic
c. Temporal scope: Seasonal or annual, as recent as possible
d. Relevance to the development of energy hubs in the North Sea

The inventory of available information was sorted, narrowed down and checked for completeness. In case there was no data (publicly) available for the defined parameters, experts from Rijkswaterstaat, Wageningen Marine Research and/or NIOZ were consulted to check for potential additional information. A final list of relevant publications and spatial data was the outcome of this step (Annex 2).

2.3.2 Layer definition

A commonly used method to look at the ecological or environmental impact of activities or systems in the marine environment is the interaction of stressors and receptors. Stressors are those parts of an activity or system that can stress or harm the marine environment. Receptors are those parts of the ecosystem that are affected (stressed) by these activities or systems. In the context of NSE, the development of an energy hub (and its individual activities) can be a stressor that affects marine animals, their habitats, oceanographic processes, or ecosystem functions. To apply this concept in the NSE Atlas, different *trophic levels* have been defined as a proxy for ecological values. Trophic levels are functional groups of species within the ecological system distinguished through their food requirements, i.e. food web. Figure 2 provides a visual display of species and species groups as trophic levels (Pint et al., 2021).

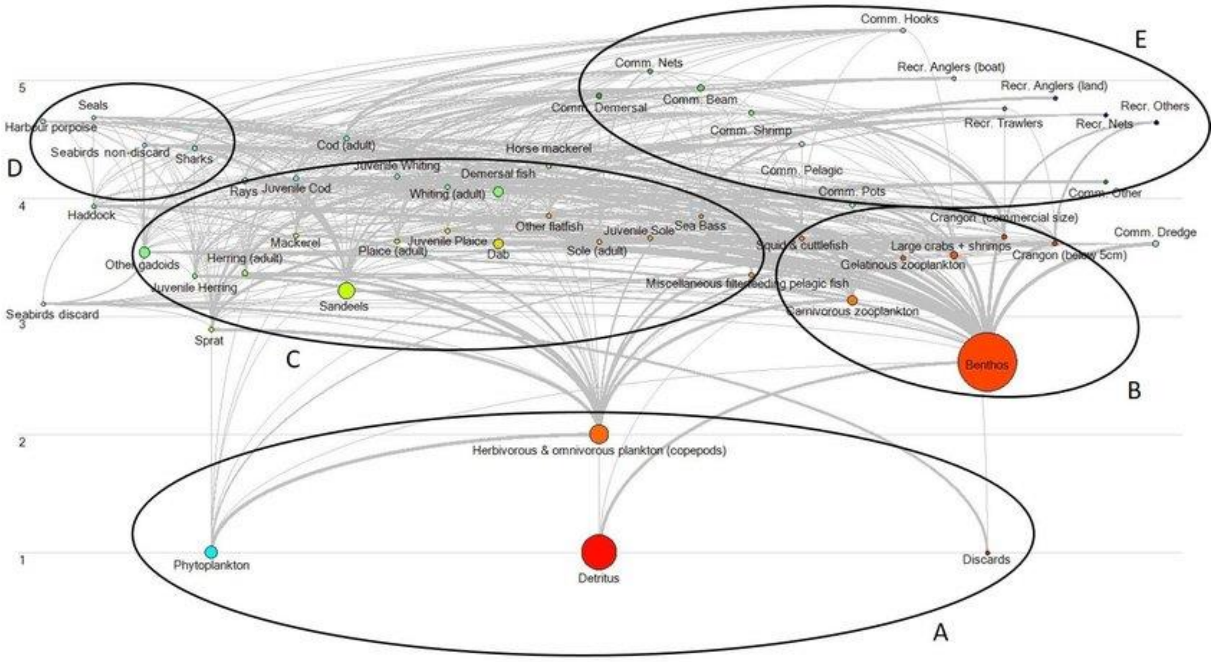

Figure 2: Ecopath model of the North Sea, including species and species groups as indicator for marine ecoystem functioning (Pint et al., 2021). The Y-axis contains the trophic level groups categorized as level 1 to 5. The encircled species groups have been combined as A to E by Pint et al.

This method of applying trophic levels is in line with the distinctions made in the WOZEP[6] programme and legal protection levels, and they were outcomes of the study in NSE2 (see also 1.3 Relation to other WPs and outline). The species groups that were applied are considered to be key indicators for marine ecosystem functioning in the North Sea. Refer to the studies from NSE2 as mentioned in 1.3 (Relation to other WPs and outline) for an initial assessment of how these species groups are affected (positively or negatively) by potential developments relating to the energy transition.

The following map layers were defined:

1. Primary production
2. Benthos
3. Fish (incl. elasmobranchs)
4.+5. Marine mammals (cetaceans and seals)
6. Seabirds
7. Bats

A more detailed description of each layer group and its relevance to this work package is provided in the results section below (2.4).

The most relevant literature and available spatial data were identified (e.g., recent maps showing an entire layer group or a relevant key species of a layer group) and prioritised in the data collection step. Map layers displaying individual (key) species were selected based on their protection status under Dutch law, namely under the Wet natuurbescherming (Wnb) Art.3.1, 3.5 and 3.10.

[6] WOZEP (Wind op zee ecologisch programma is the Dutch Governmental Offshore Wind Ecological Programme on the behalf of the Dutch Ministry of Economic Affairs and Climate (EZK). Website: https://wozep.nl/

2.3.3 Peer review

Alongside the data acquisition, intermediate results were shared with some NGOs for a peer-review. We have received peer reviews on layer definition and map selections by Natuur & Milieu, The Rich North Sea (DRN), Stichting De Noordzee, and Dutch Marine Energy (DMEC) (Annex 1). Peer review comments and suggestions were considered in the final selection and development of ecological layers and given potential future expansions of the NSE Atlas.

2.3.4 Data collection

Once all relevant and available data was identified, the available spatial data was obtained. For this purpose, we contacted the authors of publications to obtain the spatial (preferably GIS) data and requested their permission to include it in the NSE Atlas. The released data was standardized to meet the defined design criteria of the NSE Atlas and was stored together with the metadata.

2.3.5 Development of map layers

The acquired map layers for inclusion in the NSE Atlas were transformed into the appropriate format (geojson or raster) where necessary and accompanying symbology and metadata information was prepared in close consultation with WP6 and developers of the NSE Atlas.

Alongside the map layers themselves, we prepared supportive informational texts in the shape of description panels containing: General information on trophic levels and North Sea ecology, specifics on layer groups or key species, disclaimers on how to read and use the maps properly following the author's recommendations, as well as the data source and referencing. These panels are displayed next to the ecological layers in the NSE Atlas to support the spatial data displayed.

2.4 Results

In the following section, the results from activity 1 are described. An overview of which layers/ layer groups were available for this work package and included in the Atlas is given in Table 1. For each layer group, its relevance for the NSE program is described in the results, followed by a description of layers considered and selected for the Atlas.

Table 1: Overview of ecological layer groups and their availability in NSE phase 4

Layer	Type	Region	Availability status
Primary production	Seasonal patterns	NEA	Not included (uncertainties in modelled data)
Benthos	Macro-/megabenthos species richness	DCS	Included
Fish (sharks & rays)	Species distribution/ density	NEA	Not included (lacking data or under development)
Marine mammals	Seasonal predicted density of harbor porpoise	NEA	Included (Seal data is pending)
Seabirds	Wind farm sensitivity index (WSI)	NEA	Included
Bats	Spatiotemporal occurrence	DCS	Not included (available at end of 2022)

2.4.1 Primary Production

The first trophic level in the marine food web is primary production, which is the synthesis of organic compounds from CO_2 through photosynthesis or chemosynthesis. It is the food base for so-called primary consumers like zooplankton, crustaceans and small fish. The effects on primary production from the (large-scale) development of offshore structures are still subject to recent research. Changed hydrodynamics due to large-scale deployment could influence the distribution of primary producers locally (Slavik et al., 2019; Floeter et al., 2017).

The Copernicus programme[7] funded by the European Union provides daily mean Chlorophyll-alpha and net primary production maps of the North-East Atlantic in the 'wms' format (Mercator Ocean International, 2021). However, since we focus on seasonal to annual maps, this data is not useful without manipulating it, hence it was not included (see also paragraph 2.3.1).

The spring primary production model used in Van Duren et al. (2021), which has focused on the large-scale development of offshore wind farms (OWFs) using the Dutch energy plans for offshore wind, was considered an option, however, this map is currently not available due to remaining uncertainties in the underlying hydrodynamical model. Other resources in literature and public databases have been investigated but no suitable alternative for spatial data of primary production of the North Sea has been identified.

2.4.2 Benthos

Benthos is the community of organisms that live on, in, or near the bottom of the sea. They include several species groups like shellfish, worms, crabs and starfish, to name a few and are an important food source for many larger animals. Any human activity impacting the seabed, like constructing platforms or laying pipelines and cables, can impact benthic communities. At the same time, platforms and OWFs can increase local benthic biodiversity by providing a hard substrate and shelter from (bottom trawl) fisheries. (Lindeboom et al., 2008)

Benthos constitute different trophic levels based on their type: While filter feeders (like mussels) feed on organic matter from the water column, some larger species like the sea star are predators (Parzanini et al., 2018). We defined benthos as our second trophic layer group since they constitute an important food source to many fish species and several marine mammals including seals, and also seabirds.

Due to the high species richness of benthos in certain regions of the North Sea, it is not feasible to visualise distribution maps of individual benthos species. Instead, the WUR species richness maps for macro- and megabenthos are used based on spatial data published in Lindeboom et al. (2008), which is the most recent benthos species richness data made available (Figure 2). The included maps display macrobenthos (organisms > 1 mm) and megabenthos (organisms > 7 mm). Both groups display biodiversity in taxa per sample, which is the number of different species collected at specific sampling locations in multiple years and extrapolated for all other locations. Note that these maps do not indicate how many organisms of each species were found. The macrobenthos maps are derived from BIOMON boxcore sampling data by RWS/ MWTL. The megabenthos maps are derived from NIOZ Triple-D sampling data.

---

[7] https://resources.marine.copernicus.eu/

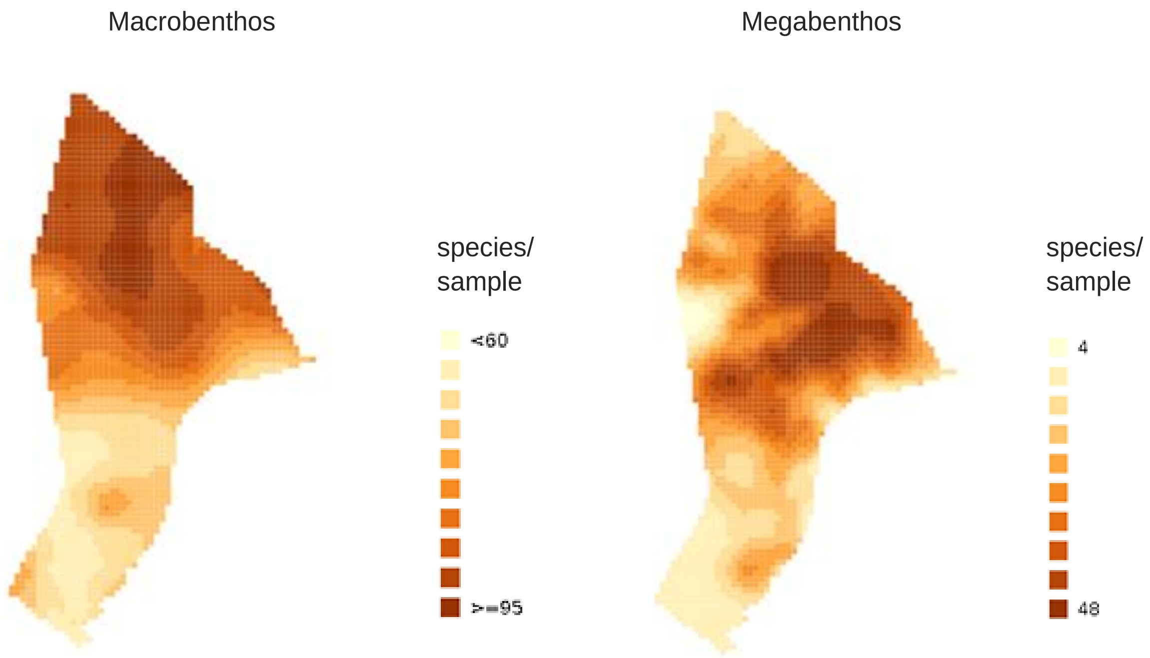

Figure 2: Macro- and megabenthos layers based on Lindeboom et al. (2008).

In addition, it was attempted to source maps visualising macrobenthic biomass (quantity and weight of organisms) as an addition to the species richness layers. Our request for this data including international benthos data as published in van der Wal et al. (2011) could not be processed in time due to different international partners being involved and holding rights to the data. This requires further collaboration with international partners (see recommendations).

Peers advised looking further into options to retrieve data from more recent Triple-D and macrozoobenthos surveys, and to contact The North Sea Net Gain project, which is currently working on a standardised benthos database. While this was not doable in time for this stage of the project, it is a consideration for further development of ecological layers in the NSE Atlas (see recommendations).

2.4.3 Fish (sharks, skates and rays)

Fish, as our third trophic group, and in particular elasmobranchs (sharks, skates and rays) are sensitive to the effects of electromagnetic frequencies (EMF) emitted by submarine cables transporting electrical currents (Taormina et al., 2018). Elasmobranch are protected through several international policy frameworks (e.g. CITES, CMS, SPAW protocol). Therefore, we aimed to include this species group in the NSE Atlas. However, unfortunately, much data is lacking. We inquired for spatial data from the European Elasmobranch Association (EEA/NEV) and WUR, but currently any relevant spatial data on this topic is lacking or in development. We also considered using spatial data from the International Bottom Trawl Surveys (IBTS), however, these surveys focus on commercial fisheries and are hence mostly interesting to include from the perspective of fishing exclusion zones in and around offshore structures. This has not been a focus of our work package in this phase of the programme and has therefore not been included.

Regarding spatial data on fish, the authors of the 2015 Fish Atlas were contacted (Heessen et al., 2015) for maps of the North Sea depicting fish taxa/haul and the average number of fish/haul. However, the authors advised us against using those datasets for our purposes due to strong variations in the number of hauls per location and the fishing gear used, creating bias (N. Daan & H. Heessen, personal communication, 2021). In addition, and similar to the above, this data is from fisheries-dependent research and therefore less relevant in the scope of this work package.

Peers advised considering the spatial data published by Sguotti et al. (2016) on elasmobranch. While this publication is interesting to look at when analysing the development of elasmobranch populations in the North Sea over time (100+ years of data), it does not hold sufficient spatial and temporal resolution for our purposes.

2.4.4 Marine mammals

Cetaceans (whales, dolphins, and porpoises)
There are several cetaceans listed in the Habitat Directive Annex IV, thereby being protected under the Wet natuurbescherming Art 3.5. However, only four of them are native to Dutch waters: The harbour porpoise (*Phocoena phocoena*), minke whale (*Balaenoptera acutorostrata*), Atlantic bottlenose dolphin (*Turiops truncates*) and the white-beaked dolphin (*Lagenorhynchus albirostris*).

Harbour Porpoise
The harbour porpoise is a top predator and amongst the most common marine mammals in European Atlantic waters. Their distribution in the North Sea is mainly driven by the location of prey hotspots. These in turn are influenced by varying environmental conditions. Harbour porpoises are considered a key species in the marine environment and receive national and international protection through several legal frameworks. (Gilles et al., 2016).

The harbour porpoise is a relatively well-researched cetacean of the southern North Sea. There are indications that the harbour porpoise is significantly disrupted by pile-driving activities during the construction of wind farms (Dahne et al., 2013). Literature indicates that the harbour porpoise population moved southwards in the last decades (Peschko et al., 2016), increasing its importance to the NSE research programme.

We have included predicted density maps from a species distribution model (SDM) of harbour porpoise in the Southern North Sea over summer as published in Gilles et al. (2016). They combine data from SCANS I, SCANS II and regional survey data sets, and environmental variables (e.g., temperature), as well as food availability, were taken into consideration (Gilles et al., 2016). Following the authors' recommendation, we included the summer layer in the NSE Atlas, since it has the lowest statistical uncertainty and biggest survey effort (Figure 3). In addition, summer is the main reproduction season for harbour porpoise in the North Sea (with mating season between June and September and birth periods from June to August) providing the greatest risks to this species from human activities (Kesslering et al., 2017).

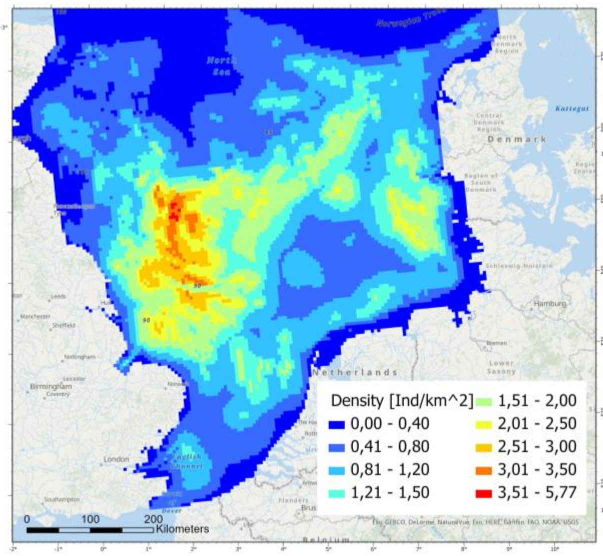

__Figure 3:__ Harbour porpoise predicted density layer for summer, based on Gilles et al. (2016)

Other Cetaceans

We considered the inclusion of spatial data on the minke whale, Atlantic bottlenose dolphin, and white-beaked dolphin from the Marine Ecosystems Research Programme (MERP) datasets (Waggitt et al., 2020). These maps visualise monthly densities for each of these species in the North Sea. The maps are made from 38 years of survey data (1980-2018) that was standardized and combined. Using these maps, however, posed two main issues. First, we would have had to choose individual months or construct our maps from multiple months to depict seasons and creating maps from literature is out of scope for this activity (due to potential biases, peer reviews required and effort involved). Secondly, the large timespan of data combined in the maps distorts the perspective of current distributions in reality.

Seals

The grey seal and harbour seal are protected under the Wnb Art. 3.10. Seal tracking data within the last decades has revealed that seals travel long distances offshore for foraging or even as a form of migrating (Brasseur et al., 2010). They appear to react sensitively to pile driving activities (Aarts et al., 2018; Russell et al., 2016).

TNO, Rijkswaterstaat and Wageningen Marine Research are currently developing seal maps similar to the ones published in Brasseur et al. (2010) and Brasseur et al. (2012). The new prediction maps should be published and made accessible in 2022, however we have not been able to source these updates yet.

2.4.5 Birds

The North Sea is a primary habitat for seabirds. The rollout and planned upscaling of Offshore Wind Farms (OWFs) pose a serious threat to several bird species through habitat displacement and collisions (Leopold & van der Wal, 2021). The Dutch coastal waters are home to large populations of multiple seabird species and they receive national and international protection through several legal frameworks. In addition to obligations from the Wet Natuurbescherming (Wnb) Art. 3.1, The Netherlands follow their obligation under Art. 4.1 and 4.2 of the Natura 2000 Birds Directive to protect regularly occurring migratory and resident bird species. This directive applies to several seabird species. The MWTL programme[8] conducts annual seabird surveys on the DCS (most recent: Fijn et al., 2020), publishing spatial data per species and month. These datasets could be used, however, they require choosing individual bird species and months, or combining different species to classifications (e.g., pelagic seabirds, coastal foraging birds, benthic foraging birds) and combining different months to seasonal maps. This would require the creation of maps and is out of scope in this phase of the programme due to potential biases, peer reviews required and the effort involved. The MERP database (Waggitt et al., 2020) also contains monthly density maps for 12 seabird species over the North-East Atlantic, posing similar challenges as the MWTL data.

Considering the above-mentioned complications and taking the recommendation of multiple experts and authors into account, the seabird Wind farm Sensitivity Index (WSI) map is included as our bird layer (Leopold & van der Wal, 2021) (Figure 4). In this index, sensitivity is defined as the mortality risk of seabirds due to collision with or displacement by offshore wind farms, in relation to the species' overall population size. It was calculated and combined for over > 25 seabird species (Leopold & van der Wal, 2021). Note that this map does not include migratory (land) birds or bats, which are also affected by OWFs.

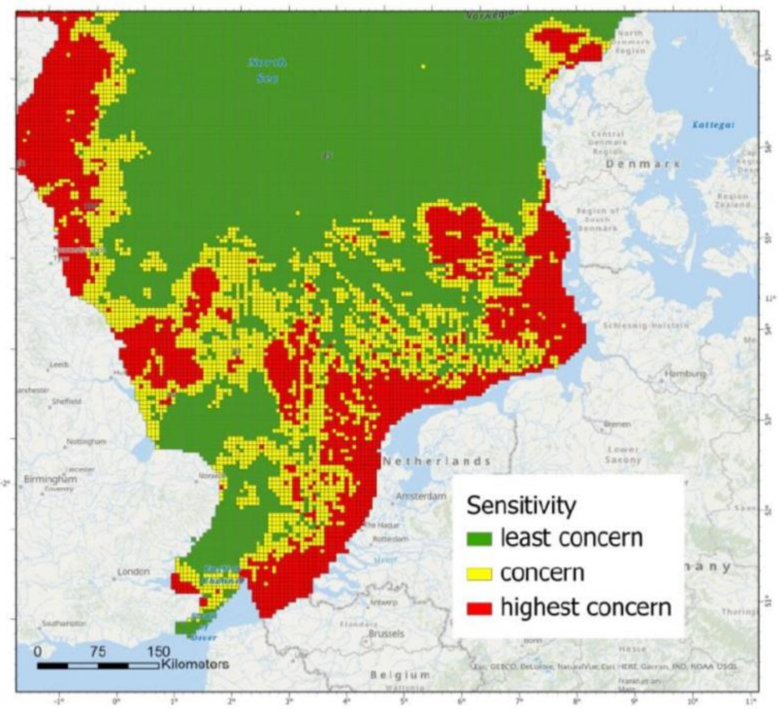

Figure 4: Seabird Wind farm Sensitivity Index (WSI), based on Leopold & van der Wal (2021)

The above WSI map has been updated in 2022 and this latest version has been included in the NSE Atlas.

2.4.6 Bats

In recent years, research efforts have increased to monitor bats foraging or migrating over Dutch waters and the North Sea. Especially the nathusius' pipistrelle (*Pipistrellus Nathusii*) is a long-distance migrant that is frequently detected close to offshore platforms and wind parks in autumn (Lagerveld et al., 2019), and it is protected under the Wnb, Art 3.5.

---

[8] MWTL (Monitoring Waterstaatkundige Toestand des Lands) is a programme to monitor the status of water bodies in The Netherlands

WOZEP is currently conducting a spatio-temporal analysis of bats offshore based on acoustic monitoring data. It is expected to be published and accessible by the end of 2022. Perhaps this map can be included in the next phase of the NSE program.

2.5 Discussion

Below is a discussion of research questions, applied method and results.

2.5.1 Availability and quality of data

While a good amount of research has been conducted on benthos, harbour porpoise, and birds, there are still severe knowledge gaps regarding other marine mammals, fish (independent surveys) and elasmobranchs and primary production. The availability and quality of data for this activity were restricted considerably by the factors below. See also Chapter 4 for conclusions and recommendations.

- Knowledge gaps/ lack of available published spatial data and scientific surveys.
- Long data retrieval processes due to multiple right-holding parties involved, especially for international data.
- Scientific uncertainties and biases in some of the (published) datasets raise concerns and hesitations by authors to share them in the NSE Atlas and the context of decision-making processes.
- Ongoing research and unpublished data.
- Outdated data and data of insufficient spatial scope.
- Time and budget limitations within this work package.

2.5.2 Selection of data

In preparation for considerations regarding the selection of energy hub locations, and before assessing the potential impacts of those energy hubs on the marine environment, an overview (when available) of relevant species and ecosystems and their current distribution in the North Sea is crucial.

The perception of what data is necessary to support the selection of energy hub locations is inconsistent amongst peers, stakeholders, and the scientific community. From a scientific perspective, a selection of single species and isolated trophic levels is hardly justifiable in light of the complex co-dependent relationships in marine ecology. Additionally, knowledge gaps are seen as uncertainties that must not be ignored and the precautionary principle (choosing the most cautious option in case of uncertainty) is highly valued. On the other hand, the energy transition is moving at a fast pace and decisions need to be made soon. This leads to a demand for readily available, simplified information that can be used as a basis and starting point in decision-making processes.

Finally, the results from this activity demonstrate that the available datasets consist of varying types of data. Data is available for single or multiple (groups) of species, selection criteria are not uniform, and in most cases, specific impacts from energy-related activities in the context of North Sea Energy are lacking. Furthermore, the available geographic data from research is either raw, time-averaged, indexed, interpolated or modelled. The data type depends on the research aim, research method and choices in data processing.
Refer to Chapter 4 for recommendations for some of these inconsistencies in data.

In this activity, we attempted to compromise in the selection of layers by (i) considering trophic levels assumed to be directly affected by offshore structures and related activities and (ii) focussing on threatened and protected species given conservation targets and legal obligations. However, this approach has not undergone a scientific peer-review, and continuous efforts and peer-reviewed assessments are desirable if more ecological layers were to be added to the NSE Atlas in the future.

3 Potential methods to estimate ecological values of existing offshore structures

3.1 Scope and purpose

The purpose of this activity is to investigate how ecological values of existing offshore structures can be determined and what the most feasible methods are to estimate those values for the energy transition in the North Sea. With this study, we aim to support decision-making in choices between decommissioning, re-use or abandonment.

The geographical scope of this activity are methods used in research on the North Sea region with a focus on the Dutch Continental Shelf (DCS). This scope has been applied to reviewing the literature, obtaining monitoring data, selecting methods and consulting experts. The most recent literature and methods have been selected for assessment and comparison in this report. Where possible, literature from 2010 and before was avoided. Methods still under development and studies in progress were included (and are mentioned as such) to draw attention to potential innovative and future solutions.

Regarding ecological values of offshore structures, the focus of this study lies on the submerged parts of a structure and their potential (direct and indirect) value for marine species (benthos, fish, marine mammals, seabirds) and ecosystems. Within the scope of this work package, potential adverse (or negative) effects on marine ecology are only touched upon. Environmental considerations such as (the avoidance of) atmospheric pollution and environmental hazards or changes in hydrodynamics and sedimentation through the presence of structures are excluded from the scope of this study (see also 4.2 Recommendations).

An assessment of methods is conducted by investigating and comparing the different methods available to estimate ecological values of offshore structures in the North Sea. Following a comparison of methods, they are assessed for feasibility to provide recommendations on which methods are the most suitable to estimate ecological values of offshore structures in the context of the NSE program. This methodology study is restricted to the scope and purpose of this work package and is non-exhaustive.

Note that the focus of this study is on *existing* offshore structures, not new structures. Therefore, newly built energy hubs creating so-called energy *islands* in the North Sea using sand or rocks are out of scope of this study (see also 4.2 Recommendations).

Key stakeholders for this activity and deliverable are platform and grid operators, policy makers, NGOs, and the general public.

3.2 Research questions

Activity 2 was conducted based on the following research questions:

1. How do existing offshore structures add ecological value to the North Sea?
2. Which methods exist to estimate ecological values of offshore structures?
3. What are the most feasible methods to use in the context of NSE?

3.3 Methods

To explore potential methods to estimate ecological values of existing structures, multiple steps have been taken. Information and methods were collected from literature, as well as through collaboration and consultation of experts, and all information was brought into a logical structure in preparation for this report.

3.3.1 Collaboration with partners and stakeholders

During the start-up of this phase in the programme, the WP4 team has discussed the possibility of collaborating with Wageningen Marine Research (WMR) since they are involved in several studies on this topic. Even though WMR has not joined this phase of the programme as a partner, several meetings to exchange knowledge, and discuss synergies and intermediate results were held with experts from WMR as well as from other institutes and companies (see Expert consultations). In addition, we made use of the NSE network and exchanged insights with other work packages of the NSE program.

Platform operators were contacted to obtain inspection materials (image material and video footage) that could potentially be used to estimate ecological values of existing offshore structures. We aimed to gather inspection materials from various types of structures (e.g., platforms, scour protection, cables and pipelines) located in different regions of the North Sea. With the permission of Shell, Boskalis and NAM, we shared some of their inspection footage with the North Sea 3D Project team of SAMS Enterprise to support training their software, and the results of their method were shared with us in return (see also: Expert Consultations).

3.3.2 Literature review

In preparation for this report and before consulting experts, a thorough review of the most recent literature was conducted using internal resources and the following online resources:

- Wageningen Marine Research
- Bureau Waardenburg
- INSITE North Sea
- North Sea Futures and LiNSI – Eco-Effective Strategies
- Windop zee ecologische programma (WOZEP)
- ICES
- North Sea 3D – SAMS
- Google Scholar

Literature was selected based on publication date, location of the study, quality (peer-reviewed and published), and relevance to the research question. A literature catalogue has been created in preparation for this report.

3.3.3 Expert consultations

In addition to the literature review, multiple experts have been consulted via e-mail, through meetings, or in an interview. For more information on epifouling growth on offshore structures, scientific sampling methods and ROV inspection, we interviewed Dr Joop Coolen (WMR). In a meeting with the researchers of the North Sea 3D Project (Tom Halpin, Tom Wilding, and Joseph Marlow of SAMS enterprise) we discussed the details of automated species recognition and 3D modelling using ROV footage. Anne-Mette Jörgensen (Eco-Effective Strategies) gave us an in-depth insight into related past and present initiatives (INSITE, LiNSI, North Sea Futures) as well as on stakeholder participation and implementation.

Ruben Fijn (Bureau Waardenburg) provided us with additional information on the value of offshore structures for birds and bird monitoring methods. Lisa van Nieuwkoop supported us in covering legal considerations. A list of all meetings and questionnaires conducted can be found in Annex 1 of this document. The insights from the discussions with these experts are incorporated into the results of this report.

3.3.4 Structuring of methods based on (spatial) scale

The literature review and expert consultations revealed that offshore structures can provide ecological value on different (spatial) scales. Potential ecological value of structures lies in local effects like increased biodiversity on the structure, local to regional food web effects, and effects on the connectivity between North Sea ecosystems (Figure 5). Likewise, methods to estimate ecological values of offshore structures vary in scale and objective, which makes it necessary to put them in a logical structure before assessing and comparing them.

To support an assessment and comparison of methodologies, four categories of value were defined. The first three categories describe ecological values and associated methods of existing offshore structures on a range of spatial scales:

- **Local effects;** with a focus on epifouling growth (communities growing on the structure).
- **Local to regional trophic-level effects;** resulting from (A) and the safety zone (fishing exclusion zone) around oil and gas platforms. This includes feeding, resting, breeding and spawning activities of fish, marine mammals and birds.
- **Regional effects;** with a focus on ecosystem connectivity and species range expansion.

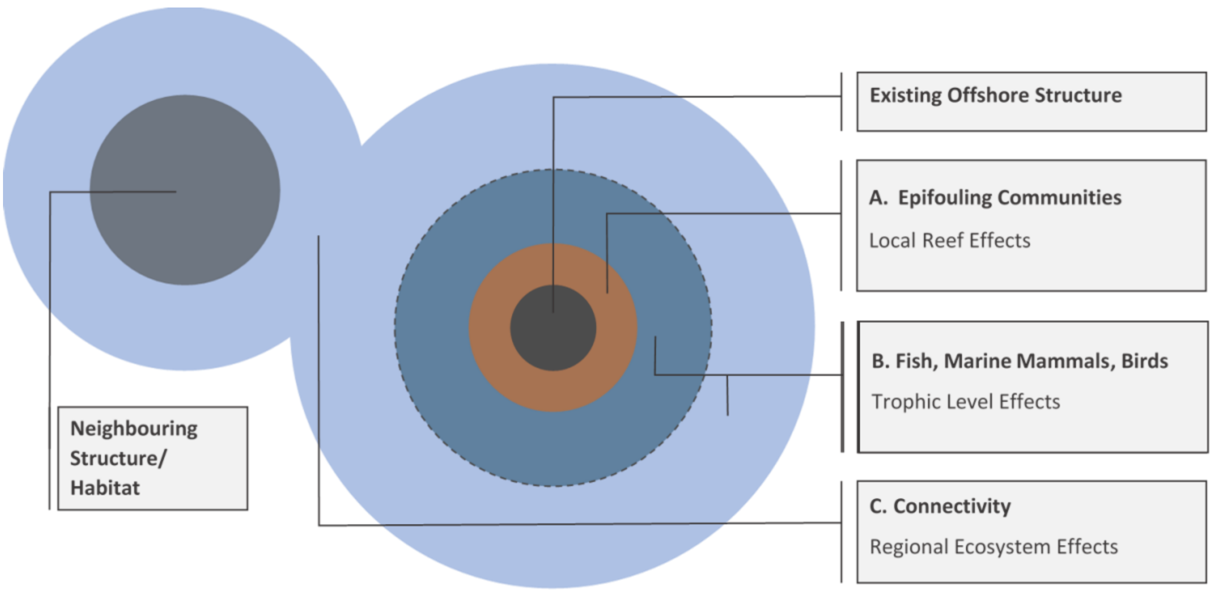

Figure 5: Ecological values of existing offshore structures on different scales (simplified)

Following a feasibility assessment of methods assessment to estimate ecological values of existing offshore structures, we will introduce methods to support decision-making processes over different decommissioning scenarios (Figure 6) in relation to ecological values of existing offshore structures. Thereby, the value of existing structures can be compared to the value of partially removing a structure or the value of a naked seabed after a full removal. This comparison is our fourth (and last) category of values and methods:

- **Comparative ecological value:** Decommissioning scenarios in comparison. Methods for the decision-making process for removal, re-use and/or abandonment of existing offshore structures.

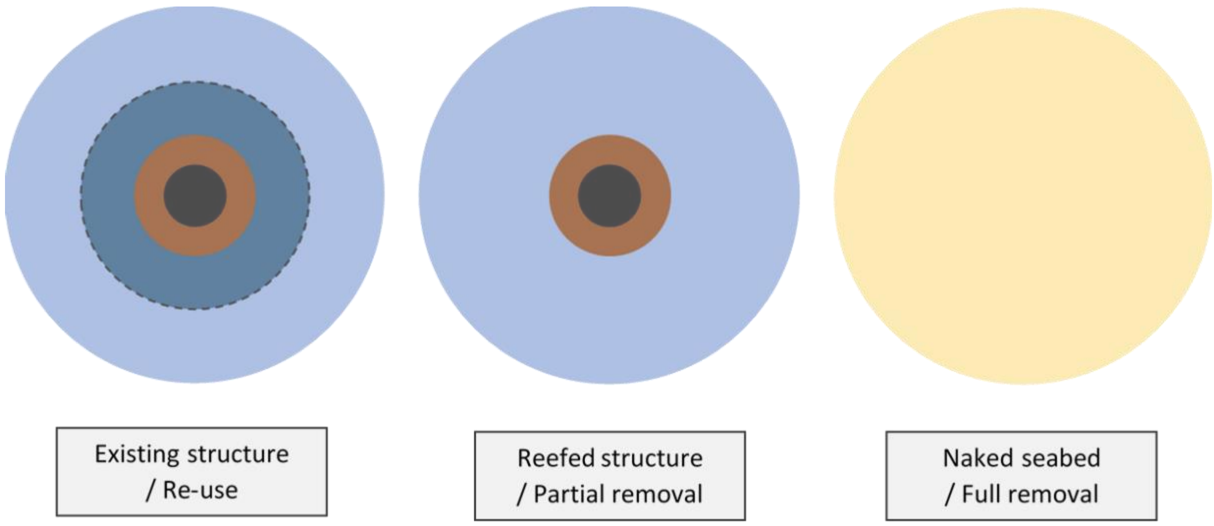

Figure 6: Comparative ecological value of decommissioning solutions in a decision-making process (simplified)

In the results section (chapter 4.5), the studied methods are assessed for each category described above. Additionally, we have described potential predictor variables (where available) for each category.

In this report, predictor variables are defined as environmental or geographical parameters which qualify as explanatory variables to biotic parameters such as species richness or biomass, based on statistical tests conducted. Understanding these predictors can (i) provide indications on why offshore structures differ in ecological value and (ii) enable predicting those values based on parameters such as structure materials, location, and depth if the respective relationships have been proven with sufficient statistical confidence.

Our approach to structure ecological values based on scaling was inspired by comparable studies of the ecological impacts of offshore structures (e.g., Verbeek et al., 2013) and by the information provided to us by literature and experts. It should be noted that this approach merely serves the purposes of this report and has not been peer-reviewed extensively.

3.3.5 Feasibility assessment

Following the results of the methodology study (see: Results), methods are assessed for feasibility in the context of the NSE program in section 4.6. Feasibility in this context was assessed based on the following (non-exhaustive) criteria:

- Availability of the method
- Standardisation of the method and acceptance in the scientific community
- Applicability to the North Sea region
- Relevance for the NSE program and roadmap
- Cost and time efficiency (where available)

3.4 Results

In this section, we will present our results for the following research questions:

1. What determines ecological value of offshore structures in the North Sea?
2. Which methods exist to estimate ecological values of offshore structures?

Potential methods to estimate ecological values and potential predictor variables are provided across four categories of measurement varying in spatial scale, ranging from local to local to regional, to regional and a comparative value, as described in methods (chapter 4.4). An overview of the presented methods is given in Table 2.

Table 2: Potential methods to estimate ecological values of existing offshore structures across varying scales

Local value: Epifouling communities	*Local to regional value*: Fish, marine mammals, seabirds	*Regional value*: Connectivity	*Comparative value*: Decommissioning scenarios
ROV footage inspection - **Trained observers** - **Machine learning**	Ship-based/ aerial-based surveys	Scientific sampling - Visual identification - DNA barcoding	MCDAs - MA - CA - NEBA
Scientific sampling	Tagging and tracking	Dispersal prediction models	
	Observations (ROV footage, platform-based, other)		
	IBTS Analysis		

3.4.1 (A) Local value: epifouling communities

3.4.1.1 The value of species growth

The jacket and scour protection of offshore structures in the North Sea are often populated by a variety of benthic organisms (species living on and/or in the sediment and sub-surface layers). Groups of species growing directly on these artificial or man-made structures (MMS) are called epifouling communities. They can form reef-like habitats and constitute a food source for higher trophic levels (i.e., organisms higher up in the food web).

Epifouling communities have the potential to contribute to European and Dutch conservation targets in multiple ways. Offshore structures provide hard substrate to species that do not thrive in/on soft sediments and are facing a shortage of suitable habitats since the disappearance of most oyster reefs in the Southern North Sea (Coolen, 2017). Reef-associated taxa often colonize artificial structures, with up to 90% of the taxa found on structures being absent in the surrounding soft sediments (Coolen et al., 2018). Biogenic reef species like *Ostrea Edulis* (European flat oyster) are protected by the European Habitat Directive. Additionally, protected and threatened species are often found on MMS. For instance, the cold-water coral *Lophelia spp.* was found to settle on most oil and gas structures (Gass & Roberts, 2006). Moreover, epifouling communities often show high biodiversity and productivity (that is, production of biomass per unit of time), thereby supporting a healthy marine environment. In Fowler et al. (2018), the provision of reef habitats and local biodiversity enhancement through offshore structures was identified as a key factor when assessing decommissioning options.

To study the epifouling growth on offshore structures (and local reef effects), the following methods (or a combination of those) can be considered.

3.4.1.2 Potential methods

To study the epifouling growth of offshore structures, different methods may be considered.

Species observation using ROV platform inspection materials

Operators of offshore structures are regularly monitoring and inspecting their platforms and infrastructure using using remotely operated vehicles (ROV) for subsurface inspection. These surveys usually consist of general visual inspection (GVI) and close visual inspection (CVI) of individual legs of the jackets and sometimes scour protection. The resulting video and/or imagery footage can show organisms growing at different depths and locations of the structure.

To use ROV monitoring materials for the scientific identification of species, the estimation of species abundances and measurement of biomass, inspection materials need to be analysed by experts. Depending on footage quality and quantity, trained observers can inspect them visually to identify the species present, estimate their abundances, and estimate growth densities on the structures. Interval scales such as the Braun-Blanquet scale (Coolen, 2017) for species abundance may be applied when estimations with high uncertainty need to be made. Because some of the taxa can be of high mobility or small size, species detectability needs to be considered in the visual inspection method. This will provide an indicator of whether species not recorded by observers are truly absent, or just appear to be absent (Coolen, 2017). Water depth and location are usually recorded by the ROV, enabling statistical tests such as correlation with species composition (Coolen, 2017). A visual inspection enables an operator's view but is not designed to facilitate scientific research (J. Coolen, personal communication, January 13, 2022).

Auto-species identification using ROV platform inspection materials

Apart from visual inspection of ROV materials, software to automate image analysis is currently under development. For instance, the NERC-funded North Sea 3D (NS3D) project conducted by SAMS enterprise is developing auto-species identification software and 3D modelling to determine the (number of) species present, species abundance, growth densities and biomass on offshore structures using ROV footage. This method follows a two-step principle: First, images and video materials are combined to create 3D models using photogrammetry. This step requires sufficient overlap of the footage materials (partially covering the same area). Secondly, a trained convolutional neural network (CNN) is applied to segment the benthic communities, and trained auto-species identification software is applied. Species-specific densities acquired from aquarium experiments are used to calculate biomass from a calculated total volume. This software is currently trained with the North Sea and UK ROV footage. As mentioned in the method description, we had also provided them with inspection materials (Shell, Boskalis and NAM) and intermediate results of species identification and 3D models were presented to us in turn. Correlations with depth and location are continuously conducted to identify potential predictors (J. Halpin, T. Wilding & J. Marlow, personal communication, December 13, 2021).

Wageningen Marine Research (WMR) is currently developing similar software to identify individual species and species aggregations using machine learning. Their software is trained using not only ROV footage but also other types of image and video materials, including material retrieved by drones. Two laser lines need to be projected on the seafloor to estimate an individual's size and to qualify it for species identification following pre-defined rules. Identification on different taxonomic levels is being tested. As with the NS3D software, the abilities of the WMR software also heavily rely on the quantity and quality it was trained with (S. Glorius, personal communication, January 13, 2022).

Potential imitations of using ROV footage as input material for auto-species identification software lay in the quantity and quality of available footage. A resolution lower than higher definition (HD), outdated ROV technology and insufficient or inconsistent coverage of a structure can make it difficult to identify species and to estimate species richness and growth density/ biomass on the structure.

Scientific sampling
Another more traditional approach to investigating the benthic communities growing on offshore structures is taking samples (*in situ*). Such surveys can be conducted by professional divers as part of operator inspection, repair, and maintenance (IRM) activities, or through independent scientific research. Different methods have been employed for the sampling itself, like sampling with specific mesh-size nets or with a surface-supplied airlift sampling system (Coolen et al., 2018). Samples may be taken in various depths and geographical transects, random, or in areas of special interest. This method can both be employed on the jacket and scour protection and has been tested both on oil and gas platforms and offshore wind farms (Coolen et al., 2018). Additional data such as material type, structure complexity, age and orientation can be recorded simultaneously when using this method (Coolen et al., 2018).

The benthic samples have to be sent to a laboratory for species identification, recording absence/presence, taxa per sample, species abundance, and also sampled biomass. This method enables identifying smaller species and those hidden to an ROV when they are growing underneath other species (which is often the case with epifouling communities and biogenic reef species). In addition, calculating productivity (biomass, abundance, biodiversity) is only possible by sampling data.

Data gathered through sampling may also provide important information for future research questions, for instance on ecosystem services or behaviour analysis (J. Coop, personal communication, January 13, 2022).

Potential limitations with regard to species size and mobility as well as the level of uncertainty are determined by the specifics of the chosen sampling method and sampling conditions. Another limitation of this method is the need for professional divers, as well as practical and safety measures restricting surveys to shallow waters (<~30 meters) and favourable weather conditions (J. Coolen, personal communication, January 13, 2022). WMR is working on the development of improved remotely operated vehicles (ROV) with a robotic sampling mechanism which could counteract such challenges (J. Coolen, personal communication, January 13, 2022).

By upscaling sampling data in a statistical model, overall species richness and biomass on the structure can be estimated. Potential correlations between species data and environmental/structural parameters may be analysed.

Predictor variables
Several variables have been identified by research as potential predictors for differences in epifouling growth between individual structures. These potential predictor variables include the geographical location of a structure within the North Sea, the depth profile of a structure, and the structure complexity (type).

Geographical location and site-specific traits can influence which organisms settle on a structure. In Fowler et al. (2018), experts agreed that the introduction of artificial hard substrate is more valuable if the structure is located where natural hard substrate used to exist. While Coolen (2017) determined that species richness at offshore structures in the North Sea decreases with distance from shore, Schutter et al. (2019) found 80% dissimilarity in species groups present between structures in the Southern North Sea and the Northern North Sea. More species were found in the northern group, whereas within one region, species richness and species diversity were relatively uniform. These differences are also suspected to be the result of differences in marine larvae streams (Schutter et al., 2019), which will be discussed further below.

Multiple studies have found that there is a correlation between the type and number of benthic species present on a structure and water depth. Coolen (2017) described a strong non-linear effect of depth on species richness, due to the verticality of offshore structures providing a wide range of environmental conditions (light, turbulence, temperature) (Schutter et al., 2019). Coolen et al. (2018) have described how species richness is highest at intermediate depth (15-25 m for structures in the Southern North Sea), whereas Schutter et al. (2019) have found species richness to be highest in the bottom zone for structures in the shallow southern North Sea. The shallow, intertidal zone of a structure appears to attract more non-indigenous species than its deeper parts and resembles the naturally occurring hard-substrate communities less (Coolen et al., 2018).

Structure complexity is assumed to increase species diversity and productivity (Verbeek et al., 2013). As for the structure material, no significant impact of differences in material was found by Coolen et al. (2018). However, species composition was significantly impacted by it. While some species, mostly so-called modifiers, could be found on all types, other species preferred one material over the other (Coolen et al., 2018).

3.4.2 (B) Local to regional value: Fish, Marine Mammals, Birds

The value of food and shelter

As mentioned before, the hard substrate of offshore structures attracts epifouling communities that act as artificial reefs. Thereby, several reef services are being provided to the marine fauna of the North Sea, and positive effects on higher trophic levels (organisms higher up in the food chain) may occur.

First and foremost, epifouling communities provide rich feeding grounds. Indications for higher occurrence and foraging/preying behaviour in fish, shark, and cetacean species close to platforms were found (Todd et al, 2020). Some species have a clear preference to forage in hard-substrate environments including artificial structures, as was found for Atlantic cod and pouting in the North Sea (Reubens et al., 2013).

Additionally, oil and gas structures in the North Sea legally require a safety zone of up to 500 m around them (UNCLOS, Dutch Mining Act), from which pelagic fishing, bottom-trawling and unauthorised shipping activities are excluded, providing areas of low disturbance to commercial fish species and species threatened by by-catch. Several fish species have been found to spawn and breed close to offshore structures (Todd et al., 2018). Fish biomass was found to be increased at left-in-place structures in California, and stocks increased at reefed structures in the Gulf of Mexico (Verbeek et al., 2013). Likewise, OWFs appear to provide reproduction opportunities and shelter to fish (Gill et al., 2020).

Through its effects on higher trophic levels, offshore structures can potentially support conservation goals for protected species (like fish, marine mammals, and seabirds). For instance, offshore structures can provide shelter for fish, these areas being inaccessible/excluded from commercial (trawl) fishing, providing potential habitat for spawning, feeding and reproduction of several marine species. These areas can support the recovery and recruitment of commercial fish species and provide a so-called 'spill-over effect'. In addition, these areas can provide feeding grounds for higher trophic levels (incl. marine mammals and seabirds). Coastal states are requested to take "proper conservational and measurement measures" to prevent their resources from over-exploitation (UNCLOS Art. 61 (2)) and any marine mammals foraging at offshore structures are protected by the EU Habitat Directive Annex IV, and international cooperation to study and conserve cetaceans is required under UNCLOS Art. 65.

To some seabird species, abandoned and re-used structures constitute potential resting and breeding sites. For instance, the black-legged kittiwake *Rissa tridactyla* has been observed to use unmanned or abandoned platforms in the Dutch North Sea as a breeding site (R. Fijn, personal communication, 2022). Multiple seabird species might use re-used structures close to the coast as breeding and resting sites, given that disturbance is minimalised and the structure features are suitable for breeding (R. Fijn, personal communication, 2022). Additionally, an increase of benthos on structures close to the coast can attract sea ducks and divers to forage, and aggregations of pelagic fish would attract gulls and gannets, inter alia (R. Fijn, personal communication, 2022).

Potential methods

Ship-based and aerial-based surveys

Long-term ship-based and aerial-based surveys along pre-defined transects as conducted by the Small Cetaceans in European Atlantic waters and the North Sea programme (SCANS) can deliver large databases on the distribution and abundance of large species in the North Sea and can cover large areas (latest SCANS report: Hammond et al., 2021). SCANS data has also been used for the predicted density map of harbour porpoise included in the NSE Atas (Gilles et al., 2016). For monitoring seabirds, aerial surveys can be used on a large spatial scale, and aerial surveys using drones can be used to cover smaller areas. Ship-based surveys cover smaller areas than aerial surveys, but observations of seabird behaviour can be made in addition to recording absence/ presence data (R. Fijn, personal communication, 2022).

For estimating ecological values of offshore structures, ship-based and aerial-based survey data have been analysed in combination with tracking data to study the effects of offshore wind farms on seals (e.g., Brasseur et al., 2010) and seabirds (e.g., Garthe et al., 2017), for instance.

Tagging and tracking

Tagging and tracking methods are widely applied to study fish, marine mammals and seabirds. When tagging individual animals, the catch location, their weight, size, sex, and life stage can be recorded. By repeating these measurements after re-capture, information can be gathered on distribution and migration, as well as changes in population demographics. Studies using tagging have been conducted on several species, for instance on the starry smooth-hound shark along the Dutch coast (Brevé et al., 2016).

Tracking individual animals with tags that record location additionally provides detailed information on movements, migration, and behaviour. Tracking has been applied to many species, including cetaceans (i.e., long-term harbour porpoise study using satellite tags, Stalder et al., 2020), seals (i.e., harbour seals in the Dutch coastal zone equipped with GPS-GMS trackers, Brasseur,2017), and seabirds (e.g., northern gannets equipped with GPS loggers in the southern North Sea, Garthe et al., 2017).

Visual observations

Different methods are available to monitor higher trophic levels with visual observations. For instance, Todd et al. (2020) investigated the occurrence and behaviour of megafauna (including large fish and marine mammals) in close vicinity of offshore structures using video materials from general inspection ROV as well as from IRM commercial diving surveys. Based on the footage, experts identified megafauna species visually and categorised their interaction with the structure (approaching, direct contact, bypassing) as well as their behaviour (travelling, foraging, searching, interaction, other) where possible. Metadata like depth and location were recorded alongside the inspection. Structures with access to electricity can be equipped with cameras, thereby providing footage for seabird observations. (R. Fijn, personal communication, 2022).

IBTS Analysis

To investigate the effect of offshore structures on fish abundance, IBTS data may be used as an indicator for shifts in abundance over time for commercial fish species. Wright et al. (2020) demonstrated how IBTS data combined with independently retrieved tagging data can be analysed for correlations between offshore structures and the abundance in and spawning of selected fish species.

3.4.3 (C) Regional value: Connectivity

The value of larvae

Which species have the potential to populate offshore structures is largely determined by marine larval streams passing the structure (Schutter et al, 2019). These larvae originate from adult individuals in nearby habitats and are being transported through the North Sea by water streams such as tidal flows, mean flows and turbulent dispersion as part of the zooplankton (Thorpe, 2012). Benthic larvae, called meroplankton (Ershova et al., 2019) differ in swimming behaviour (passive/ active transport) and in the time until they start settling (Henry et al., 2018).

Through these marine larval streams, offshore structures are being connected to ecosystems in close vicinity and can further distribute larvae through the epifouling communities growing on them. Through these processes, offshore structures can play a major role in connecting otherwise isolated communities and habitats, called ‘connectivity’ in ecosystem functioning. Moreover, they can enlarge the natural range of individual species, making them so-called “stepping-stones” to new habitats (Coolen et al., 2017). Due to the geographical range of offshore structures, their role in connecting habitats and extending habitat ranges could be significant, despite the relatively small total area they are covering in the North Sea (Schutter et al., 2019). It should be noted that connectivity and range expansion applies both to indigenous and non-indigenous species.

Studying connectivity and range expansion with regard to offshore structures can help achieve several conservation goals. Connecting smaller and isolated (potentially previously disrupted) habitats or populations can positively affect associated ecosystems by catalysing genetic exchange and by enhancing ecosystem resilience (Henry et al., 2018; Schutter et al., 2019; Fowler et al., 2020). On the other hand, facilitated range expansion of non-indigenous species through offshore structures should be studied carefully (Adams et al., 2014; De Mesel et al., 2015; Couton et al., 2019).

Potential methods

To assess the impact of offshore structures on connectivity and range expansion (regional ecosystem effects), larvae streams passing by as well as originating from the structure should be studied.

Scientific sampling

There are multiple ways of sampling larvae from the water column around structures. Samples can be taken from the water column using nets and identified morphologically in the laboratory to the lowest taxonomic level possible (Ershova et al., 2019). While this method is readily available, results retrieved can be characterised by a high uncertainty factor, since there are several knowledge gaps currently existing concerning this method. Many species are difficult to distinguish in the larvae state, larvae can show phenotype plasticity, and many species have not been identified yet (Webb et al., 2006; Couton et al., 2019; Descôteaux et al., 2021).

For species that are difficult to identify morphologically, DNA barcoding can be applied to identify larvae if sufficient reference libraries are available (Ershova et al., 2019).DNA barcoding is a method that uses DNA sections to identify species, using polymerase chain reaction (PCR) amplification and partial sequencing (Webb et al., 2006; Anand et al., 2019). Through DNA barcoding, it is possible to identify larvae to species level, to determine species richness (Descôteaux et al., 2021), and to identify larvae more quickly than through morphological identification (Webb et al., 2006). DNA barcoding can also be used to study the spatial spread of non-indigenous species (Couton et al., 2019).

Dispersal prediction modelling

Larvae dispersal can also be predicted using models. Henry et al., 2018 conducted an intensive study in which the potential for connectivity between oil and gas platforms was tested for coral species using a biophysical dispersal model. Oil and gas platforms across the North Sea were modelled to disperse coral larvae at distinguished temporal intervals. Following the approach of individual-based modelling for particle tracking, the spatial dispersion of the larvae released in the model was computed in real-time. Mean depth of coral growth (estimated from ROV materials), species-specific larvae swimming behaviour and age of settling competency were considered in the model. Based on such a model, the combined connectivity of multiple platforms, as well as individual effects, can be approximated, and analysis can be conducted on a regional scale. It should be noted that running such a model requires high computational power.

Van der Molen et al. (2018) applied General Individual Transport Models (GITM) to several species to investigate connectivity between offshore structures in the North Sea from 2001 to 2010. Planktonic dispersal through currents was modelled for the pelagic stages of, inter alia, the cold water coral *L. Pertusa* and the blue mussel *M. Edulis*. under consideration of hydrodynamics and diffusion as well as biotic factors including vertical migration behaviour of larvae and egg/ larvae development. North Sea sectors where defined, and potential particle receival and supply were identified for each of them, leading to connectivity maps of the North Sea. Particle tracking was generalised and simplified, limiting the level of detail resulting from it (van der Molen et al., 2018).

Predictor variables

Geographical location is the key factor when talking about potential predictors for the connectivity effect. This is related to the species-specific travel distances of larvae and the closeness of structures to other structures and relevant habitats and populations. Dispersal from a structure to its surrounding also depends on the structure height in which the adult individuals of a species prefer to settle (Henry et al., 2018).

Tidal waves can transport larvae relatively far to downstream structures, resulting in a short-term connectivity effect. To reach longer-term connectivity between (clusters of) structures, a significant concentration of larvae needs to be released by upstream platforms (Thorpe et al, 2012). Streamline flows likely result in “strings” of interconnected structures, whereas substantial tidal and potentially mean flow, as well as turbulent dispersal, is needed to spread larvae across streamlines (Thorpe et al., 2012)

On another note, meroplankton undergoes seasonal variability. Their life span exceeds in colder temperatures, influencing their dispersal range (Descôteaux et al., 2021). Additionally, larvae abundance is largest in spring and early summer, presumably due to the enhanced food availability during the phytoplankton bloom (Descôteaux et al., 2021).

With regard to studying non-indigenous species, multiple research items have demonstrated that non-native species are primarily present in the intertidal zone of offshore installations in the North Sea, whereas deeper parts of the jacket, base or scour protection resemble naturally occurring communities more (e.g., De Mesel et al., 2015; Coolen et al., 2020). This can have indications for the evaluation of different decommissioning scenarios.

3.4.4 (D) Comparative value: Decommissioning scenarios

Values of decommissioning scenarios in comparison
Up until this point, we have discussed the absolute ecological values of existing offshore structures, as we examined species and habitats profiting from existing offshore structures in different ways. Another way to look at existing offshore structures is to compare their ecological values to that of the naked seabed, or alternative decommissioning options (Figure 7), thereby determining the “net benefit” for the marine ecosystems of the North Sea. In a decision-making process regarding ‘if’ and ‘how’ existing offshore structures should be decommissioned from the perspective of nature and ecology, ecological values of each scenario should be assessed. Following that, scenarios should be compared against each other to determine the most favourable solution for the marine environment.

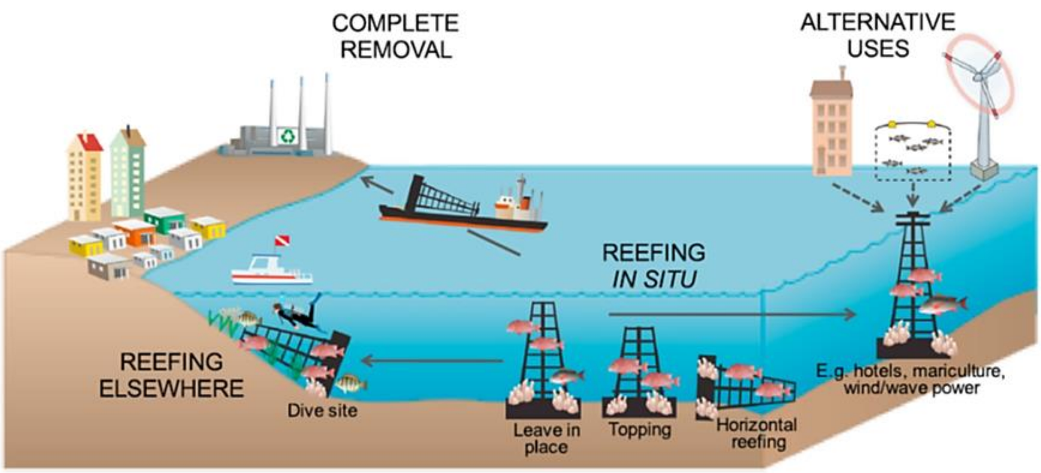

Figure 7: Conceptual overview of decommissioning options (Sommer et al., 2019)

Potential methods
The most common approach in this field for dilemmas in decision-making is the multi-criteria decision analysis (MCDA). In an MCDA, the performance of different options is ranked following a set of assessment criteria that are pre-defined by stakeholders and experts. In light of decommissioning scenarios, an assessment is conducted applying technical, financial, societal and environmental criteria with varying weights. In the following, we will focus on the ecological and environmental aspects of conducting MCDAs for the assessment of ecological values of offshore structures.

There are different types of MCDAs used for decommissioning decisions, which differ in their options-criteria-matrices based on decommissioning options considered and the underlying understanding of ecological value. Since MCDAs in Europe traditionally consider only the option of full removal due to the current legislation, the removal of structures is only assessed based on the potential negative impacts of a structure and the removal itself on the environment (Sommer et a., 2019). In contrast, countries that have tested or are frequently conducting alternative decommissioning options (such as partial removal, re-deployment, or re-use) base their decision-making matrices on the potential benefits of existing structures and the value of thereby developed ecosystems as well (Sommer et al., 2019). In the following, a selection of MCDA techniques will be introduced.

In the UK, the most common approach is to conduct Comparative Assessments (CA) based on Environmental Impact Analyses (EIAs) to decide on decommissioning. This more traditional approach is assuming that full removal of offshore structures and returning to the “natural” naked seabed state is generally the most favourable option for the environment (Sommer et al., 2019). An alternative to this method lies in Net Environmental Benefit Analysis (NEBA), which was originally designed to facilitate fast decision-making in the event of offshore oil spills. NEBA has recently been tested successfully for multiple cases of comparing different decommissioning options, for instance in the UK and Thailand (Martins et al., 2020; Sommer et al., 2019). In this approach, ecological benefits are weighed against potential negative ecological impacts and hazards. This way, leaving existing offshore structures that add biomass and biodiversity to the marine environment in place has the potential to be identified as an environmentally favourable option.

Fowler et al. (2014) promote the method of using a Multi-criteria Approval (MA) for decommissioning decisions, which is also using an option-criteria-matrix. The criteria and decommissioning options considered can be altered by experts depending on the research question and conditions. An example for environmental criteria is given in Figure 8. Like with NEBA, criteria selected for an MA can include both environmental risks and benefits of different decommissioning options, recognising potential ecological values of existing structures. This method can be applied to mixed datasets and incomplete datasets since it follows the binary principle of “approved” or “disapproved” for each decommissioning option regarding each of the criteria (Fowler et al., 2014). The approval can be given or denied by experts and stakeholders following different methods: (i) Defining thresholds for each criterion, for instance, a minimum of species that need to grow on a structure, (ii) creating semi-quantitative scales in which the least performing option(s) get disapproved or (iii) identifying which options perform below or above the average.

Criteria
Energy use
Gas emissions
Contamination
Production of exploitable biomass
Provision of reef habitat
Enhancement of diversity
Protection from trawling
Spread of invasive species
Loss of the developed community
Facilitation of disease
Alteration of trophic webs
Alteration of hydrodynamic regimes
Habitat damage from scattering of debris
Smothering of soft-bottom communities

Figure 8: Example of ecological criteria list using Multi-criteria Approval (MA) (Fowler et al., 2014)

Other methods commonly used to facilitate decision-making processes have also been looked into, including CBA (cost-benefit analysis), SWOT (strengths, weaknesses, opportunities, threats), and PESTEL (political, economic, social, environmental, legal). PESTEL is a method that has been used for decision-making processes over decommissioning questions in the past (e.g., Capobianco et al., 2021). It is typically used to compare different pathways and future scenarios within a certain macroenvironment, which makes it a potential method to be used in the context of NSE. However, ecology is often only touched upon within a PESTEL analysis and the assessment approach is kept broad, compared to the potentially more detailed ecological criteria lists created based on thorough scientific input in an MCDA.

3.4.5 Feasibility of methods

In the results sections, we have introduced several methods to estimate ecological values of existing offshore structures on different scales. In the following section, we have assessed these methods on performance in terms of feasibility for the North Sea region and in the context of the NSE program, to answer the question:

3. What are the most feasible methods to use in the context of NSE?

It should be noted that our conclusions on feasibility are derived from the non-exhaustive information gathered for this report, insights provided by experts and our own (subjective) assessment. It is recommended to further discuss and analyse the most feasible methods that best fulfil the needs of the NSE program. The upscaling of methods, future technologies and future research (e.g. on cumulative effects) should also be considered. See also 4.2 Recommendations.

Legal Feasibility

Before discussing the feasibility of methods to estimate ecological values of existing offshore structures, the legal feasibility of exercising alternative decommissioning plans such as re-use, partial removal, or leaving in place of offshore structures in the North Sea after their operational life will be briefly discussed here.

As mentioned in the introduction, the current legislation provides for a general obligation for the full removal of installations and structures in the North Sea. Under OSPAR Art. 1, the "deliberate disposal in the maritime area of offshore installations and offshore pipelines" is considered dumping. Likewise, UNCLOS Art. 60(3) states that "any installations or structures which are abandoned or disused shall be removed to ensure the safety of navigation". The IMO Guidelines[9] clearly state the general obligation for full removal in Art. 1 and the specifications in Art. 3.1 and 3.2 indicate that most structures in the southern North Sea fall under that obligation.

However, Art. 60(3) of UNCLOS also states that information has to be published on "any installations or structures [that are] not entirely removed", potentially leaving room for exceptions from that general obligation (L. v. Nieuwkoop, personal communication, February 4th, 2022). The IMO Guidelines are specifying exceptions more clearly for installations and structures that will "serve a new use" under Art. 3.4.1. This has clear indications and relevance for the activities planned within North Sea Energy (L. v. Nieuwkoop, personal communication, January 25th, 2022). Finally, Dutch legislation will change with the 2020 amendment of the Mining Act[10][11], introducing opportunities for "full or partial reuse" of mining works under certain conditions in Art. 44b. It should also be noted that a legal definition of "re-use" is lacking, leaving room for interpretation as to whether re-purposing structures as artificial reefs could be classified as such (L. v. Nieuwkoop, personal communication, February 4th, 2022).

Analysing ROV inspection materials for epifouling growth

We consider using ROV inspection materials to estimate the (local) ecological value of existing offshore structures in the North Sea a feasible method. ROV materials are readily available for different structure types and have a high spatial and temporal resolution. It has been demonstrated that a variety of ecological data can be retrieved from them by observers or using machine learning (species identification, abundance, biodiversity). Automated species identification and 3D modelling hold a great potential to inspect large amounts of footage, which is necessary to make it a feasible method for the NSE roadmap. Additionally, it could provide biomass estimates in the future.

However, although this method is deemed feasible, conditions to ROV footage apply for this method to be useful for scientific analysis. For automated species identification, diverse, high-quality footage is needed to train machine learning algorithms. It is also crucial that image and video materials of sufficient quality are easily accessible to researchers. There are several re-occurring issues encountered by both scientific observers and software developers in using ROV materials produced by operators for platform and infrastructure inspection. To successfully retrieve ecological data from these materials, literature and experts recommend that ROV (inspection) materials are standardised to the following qualitative criteria:

- Uncompressed high image/ video resolution (HD and higher, ≥1080p)
- High sampling rate (≥60 frames per second)
- Consistent (spatial) coverage of structures (vertical and horizontal coverage, 360° angles)
- Laser pointers (2 or more) on the ROV to reference organism sizes and distances
- Mindful planning through communication between researchers and ROV pilots, including instructions on chosen transects, angles and system configuration

Sampling epifouling communities

[9] IMO Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone, 1989

[10] Mining Act (Mijnbouwwet) of 31 October 2002

[11] Kamerstukken I 2020/21, 35462, Wijziging van de Mijnbouwwet

In addition to using ROV materials, scientific sampling of epifouling communities from offshore structures will continue to be necessary for the upcoming years. Species that cannot be detected from ROV materials (too small, not showing on the surface) can be detected through sampling, and biodiversity is often heavily underestimated using just ROV inspection (J. Coop, personal communication, January 13, 2022). Additionally, sampling enables recording species-specific biomasses, which is important to (i) estimate a structure's productivity and (ii) provide reference data for software development.

In principle, sampling communities from offshore structures using a professional diver is a feasible method to be conducted in the Southern North Sea due to its shallow waters. However, the posed risks to the diver make this method cost-intensive, and few divers are trained to conduct such surveys in the North Sea (J. Coolen, personal communication, January 13, 2022). Thereby, this method is not feasible for a large-scaled survey as it would be needed to examine dozens to hundreds of oil and gas platforms approaching the end of their operational life. The further development and use of ROVs to survey (and in the future potentially also to take samples) is, therefore, crucial to facilitate more extensive sampling, to cover a larger area and different types of structures at considerably reduced costs (J. Coolen, personal communication, January 13, 2022).

Regardless of the chosen method to estimate epifouling communities of existing structures in the North Sea, working closely together with prediction models will facilitate identifying data gaps and will minimise the survey effort in the future (J. Halpin, J. Marlow, T. Wilding, personal communication, December 13, 2022; A.-M. Jørgensen, personal communication, January 17, 2022).

Studying trophic level effects

The importance of offshore structures to local and regional ecology in combination with the benefits of a fishing exclusion zone requires further research. For instance, additional research is required on the bottom-up effects of local biodiversity on higher trophic levels (e.g., the bottom-up effects of biodiversity on offshore structures in relation to the effects on fish, marine mammals and birds). WOZEP has included this as a future focus for its research programme over the coming years. In addition, the potential aggregation and behaviour of organisms in and around offshore structures should be studied further. These research efforts should preferably be done through international collaboration.

As touched upon in the results section, using IBTS data to study correlations between existing offshore structures and abundance in commercial fish species is a method that could be explored, and large amounts of recent IBTS data are readily available for multiple species. However, it should be combined with independent scientific fish surveys (e.g., through tagging) to derive less biased conclusions, and potentially other methods will need to be applied to include non-commercial species.

Observations of marine mammals and large fish species (visual observations, video/ image inspection) can be a useful method to study their occurrence and behaviour close to offshore structures. These observations can provide insights into potential feeding, breeding, or spawning activities, but are often not standardised and inconsistent, which is why we do not deem it a feasible method on its own to base decision-making processes for the NSE roadmap on. Nonetheless, it could be a feasible method to support researching the potential ecological effects of offshore structures on higher trophic levels.

With regard to seabirds, conducting monitoring by installing cameras could be a feasible method for structures with access to electricity that is close to shore, emit low noise and light pollution, and have periods of little human activity on them (R. Fijn, personal communication, 2022). This could be especially interesting for structures re-used for power to gas (P2H2) production.

Tagging is a traditional method to study the movement of individual marine mammals, elasmobranchs, and birds, which makes it a useful tool to improve our knowledge of how these animals may interact with offshore structures. While it is feasible (and has been demonstrated) to use tagging in the North Sea, it is difficult to derive conclusions for entire populations or ecosystems from tagging individuals (e.g., Brasseur et al., 2010). As with observations, data retrieved by tagging can still provide useful information about the effects of offshore structures on marine mammals, fish, and birds.

Studying larvae streams

In the past years, (inter)connectivity of offshore structures has increasingly drawn attention in the scientific community, as it may be one of the keys to progressing from a local to a regional view on the impacts of offshore structures on marine ecosystems. The benefits of creating larger, connected habitats for threatened species need to be weighed against the potential risks of spreading harmful invasive species further (Verbeek et al., 2013; A.-M. Jørgensen, personal communication, January 17, 2022). Soon, many structures will need to be decommissioned within a short amount of time in the North Sea, and a more holistic view of the ecosystems in the North Sea and the potential connectivity between separate more local ecosystems (in and around offshore structures) is required. Hence, more research is needed to improve methods to investigate the role of larvae streams.

As described in the Results section, sampling larvae and identifying them morphologically is possible in principle but can be subject to inconsistency, high uncertainty and relatively low level of detail (identifying taxa instead of species) due to large knowledge gaps. The feasibility of DNA barcoding compared to morphology-based identification increases as more reference databases evolve and barcoding methods are being explored more broadly (Ershova et al., 2019). Additionally, cost-effective DNA extraction methods are available (e.g., HotShot methods, Ershova et al., 2019).

Henry et al. (2018) and van der Molen et al. (2018) have presented different modelling approaches to study connectivity through (benthic) larvae streams in the North Sea, taking species-specific traits and hydrodynamical factors into consideration. By demonstrating a large effect of offshore platforms on ecosystem connectivity, the outcomes of these studies are highly relevant to the research questions of this work package, and further exploration of larvae dispersal models is a feasible method to evaluate the connectivity value of offshore structures in the North Sea on a large spatial scale.

Assessing alternative decommissioning options

In the results section, we have introduced several MCDA methods to facilitate the decision-making process regarding the removal, re-use, or abandonment of offshore structures based on their ecological value.

To incorporate not only an assessment of potential risks and negative impacts on the marine environment and ecology but also potential ecological values of existing offshore structures, a method like NEBA or MA could be chosen. Since data on ecological values and the effects of offshore structures on the marine environment are currently still inconsistent and often characterised by knowledge gaps, MA could be a feasible approach (see also chapter 4.5.4). Conducting MCDAs with a focus on environmental and ecological criteria for structures in the North Sea could also help identify knowledge gaps and potentially make further research more efficient.

From an ecology perspective, many experts agree that the most favourable decommissioning option should be determined on a case-by-case basis (Fowler et al., 2014; Todd et al., 2020, A.-M. Jørgensen, personal communication, January 17, 2022) either for individual structures or for groups of structures. In Fowler et al. (2018), over 90% of the consulted experts agreed that if offshore structures are ecologically (inter)connected, they should not be assessed individually but as a group of structures to determine the best decommissioning option. However, applying the case-by-case approach to individual structures has hampered the rigs-to-reef campaign in California due to complicated permitting processes (Verbeek et al., 2013). This needs to be looked into further to support decision-making processes over alternative decommissioning options for the North Sea.

4 Conclusions and recommendations

4.1 Conclusions

In this work package, we have provided initial insights for the NSE program (i) to support spatial planning and hub selection by gathering spatial information on the marine ecology of the North Sea and developing ecological layers for the NSE Atlas (ii). The aim is to support decision-making in decommissioning options of existing offshore structures in the North Sea by exploring and assessing potential methods to estimate their ecological values. Following is a summary of the main conclusions from this study.

4.1.1 Spatial information to support energy hub selection

In activity 1, we retrieved and prepared ecological (map) layers based on the most recent scientific literature on marine ecology in the North Sea. These layers are added to the existing NSE Atlas and can be used in support of spatial planning of energy hub selection. In this initial effort, layers were added for benthos, harbour porpoise and seabirds and more layers can be added in the next phase of the programme.

In the North Sea Energy programme, three potential energy hubs on the Dutch Continental Shelf were defined: Hub West, Hub East, and Hub North (see Figure 8). Based on the ecological layers included, it is currently not possible to conclude which hub location would be preferred due to the least impact or due to the best potential benefits for the marine ecology of the North Sea. However, some preliminary assessments from this data are summed up below. Note that these assessments have not been peer-reviewed and it is recommended to determine the most preferable Hub location from a marine ecology perspective by enabling a more thorough assessment by subject matter experts through a more intensive collaboration or work sessions in the next phase of the programme (see 4.2 Recommendations).

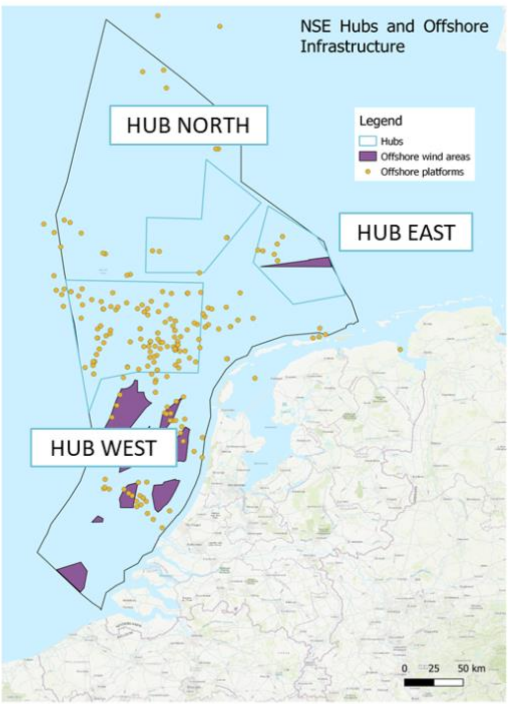

Figure 8: Potential NSE energy hub locations: Hub East, Hub West, and Hub North.

Some preliminary (non-peer-reviewed) assessments for specific species groups:

- Macrobenthos species richness is highest in the northern DCS, whereas megabenthos species richness is highest in the East. By comparing these layers to the potential energy hub locations, it could be argued that benthic species richness is lowest in Hub West, making this the favourable option with regards to benthic species richness. It should be noted that the benthos layers do not contain information on benthic biomass or specific (possibly threatened) species. In addition to this assessment, the northern DCS contains some long-living species (like the ocean quahog, *Arctica islandica*) and should best be kept undisturbed. At the same time, this could be a counter-argument for a platform in the northern areas, as it can provide benefits for benthos when being excluded from commercial (trawl) fisheries.
- The seabird Wind farm Sensitivity Index (WSI) depicts that the mortality risk for seabirds due to wind farms is highest close to the coast, and lowest towards Hub North. However, seabirds could benefit from specific types of structures as breeding, resting and foraging sites especially when closer to the coast (R. Fijn, personal communication, 2022).
- While the density prediction maps for harbour porpoise by Gilles et al. (2016) could indicate that harbour porpoise density is highest in Hub West, the uncertainty of these maps is relatively large. In turn, the MERP datasets on harbour porpoise (Waggitt et al., 2020) indicate that density is highest in the North. However, the spatial and temporal scope of the two studies differ greatly and an assessment with regard to harbour porpoise is complex.

As mentioned above, these conclusions should be considered preliminary and require a peer-review and further assessment by experts.

4.1.2 Methods in support of decommissioning scenarios

In activity 2, potential ecological values of existing offshore structures and associated methods were identified and assessed based on a thorough literature review and expert consultations, to support decision-making processes over removal, re-use and abandonment.

The results have demonstrated that existing offshore structures have the potential to provide a variety of ecological values (from local to regional), and a range of methods exist to estimate them. Several methods were identified as feasible to apply in the context of NSE, including automated species identification software and Remote Operated Vehicles. To compare decommissioning options a Multi-criteria Approval (MA) assessment could be applied.

How valuable existing structures are to marine ecology differs based on several factors, such as structure type (material, complexity) and geographical location. Currently, full removal of offshore structures and the return to a naked seabed after the operational life of an offshore structure is considered the most favourable option for the environment. This is supported by an obligation for complete removal in current national legislation. However, rigs-to-reef programs (partial removal or abandonment) abroad as well as research on structures in the North Sea have demonstrated a potential for structures to add ecological value to the marine environment, even (and especially) after their operational life. Aside from physical factors and the outcomes from research, much also depends on the perspective taken when discussing ‘ecological value’ as currently, a broadly accepted definition is lacking (due to the many different perspectives, e.g. comparing with historical baselines or considering future potentials and shifting baselines).

In the next paragraph, recommendations are provided to continue to broaden our knowledge of the North Sea marine ecology in support of decision-making in the NSE program.

4.2 Recommendations

To provide an overview, our recommendations are summed up below. These are further elaborated on in the next paragraphs.

More general recommendations and considerations:
- Continued and increased monitoring
- Continued and increased international collaboration
- Continued and increased funding

Specific recommendations for the NSE program:
- Include more and improved ecological layers in the NSE Atlas
- Study the opportunities for nature-inclusive design of energy HUBs

4.2.1 General recommendations and considerations

To initiate and support studies on the effects and potential benefits of the changes to our marine environment as a result of upcoming developments in relation to the energy transition several Dutch monitoring programmes have been developed. These are programmes like De Rijke Noordzee, WOZEP (Dutch Governmental Offshore Wind Ecological Program), KEC (Kader Ecologie en Cumulatie) and MONS[12] (Program Monitoring, Research, Nature strengthening and Species protection), to name a few. Much of the knowledge gained from these programmes have been used in the underlying studies and it is recommended to continue to do so.

Within the scope of the NSE program, it is recommended to continue and broaden the efforts to evaluate ecological values in the North Sea and where possible in an international context. These efforts should focus on evaluating existing ecological values and potential (cumulative) effects (including risks) from the development of energy hubs, as well as assessing potential benefits for nature as a result of nature-inclusive design and spatial planning. A nature-inclusive design of energy hubs is recommended to halt further degradation of marine ecosystems and more so, to provide opportunities for growth of biodiversity in the North Sea. To enable these efforts, there is an urgent need for additional funding for ecological research and more international cooperation.

This recommendation is supported by several stakeholders involved in discussions around the energy transition in the North Sea. In the webinar 'Stakeholder perspectives on North Sea system integration' organised by the NSE program on 20 January 2022, Stichting De Noordzee (represented by Heleen Vollers) acknowledged the great efforts done so far, but highlighted two important needs; 1) the importance of proper protection of nature, using the example of implementing protection measures in Marine Protected Areas to protect the seabed as a natural carbon sink and as an important recruitment and foraging areas for fish, resulting in healthy nature as well as healthy fish stocks to provide food security for humans (ecosystem services) and 2) the current lack of balance (in funding) between technological and economic incentives versus incentives and opportunities for nature. The webinar and its participants also highlighted the issue of the speed of research (on ecology) versus the speed of the transition. To better overcome the uncertainties and challenges in relation to the energy transition and

[12] MONS is a monitoring program that works in close conjunction with WOZEP and aims to increase our knowledge on impacts and opportunities in relation to the nature, food and energy transitions that influence the North Sea ecosystem, including non-protected species.

the conservation and protection of nature (and the ecosystem services it provides), this balance needs to be restored.

4.2.2 Specific recommendations for the NSE program

To support assessments and decision-making within the scope of the NSE program it is recommended to gain more insights into marine ecology that support choices in relation to spatial planning. More information is required on the spatial distribution of protected species, as well as non-protected species and ecosystem functioning in the North Sea. To achieve this, it is recommended to add more geographical layers to the NSE Atlas on marine ecology. In this effort, it is important to focus on (additional) ecological spatial data that supports decision-making in the NSE program. It is recommended to include the following when considering geographical information in relation to the NSE program.

Improved benthos hotspots

It is recommended to include improved benthos layers. Peers advised looking further into options to retrieve data from more recent Triple-D and macrozoobenthos surveys and to contact The North Sea Net Gain project, which is currently working on a standardised benthos database. These should cover the Greater North Sea.

Elasmobranch (sharks, rays and skates)

Elasmobranch, the scientific term for sharks, rays and skates, are sensitive to the effects of electromagnetic frequencies (EMF) emitted by submarine cables transporting electrical currents. Therefore, it is recommended to include maps on this subclass of fish. Peers advised considering the spatial data published by Sguotti et al. (2016) on elasmobranch. While this publication is interesting to look at when analysing the development of elasmobranch populations in the North Sea over time (100+ years of data), it does not hold sufficient spatial and temporal resolution for our purposes. For insights into the effects of EMF on elasmobranch, it is recommended to follow the developments and outcomes from the ElasmoPower project. This project is supported and funded by the Dutch Science Council (NWO) and WOZEP and specifically studies the effects of EMF on Elasmobranch.

Future projections

Where relevant and available, it would be beneficial to include maps with future projections or modelled data that visualise the effects on certain species and ecosystems as a result of the planned energy transition developments. There it is advised to include studies that focus on the upscaling of energy transition developments towards 2050.

International data

In the current study, it proved difficult to locate international scientists or gain permission in a relatively short timeframe for data-sharing and publishing. In light of the international context of the program, all layers to be included should contain data for the North-East Atlantic or Greater North Sea. To achieve this, collaboration with potential international partners is recommended. The consultation and data requests to international experts would also benefit from direct contact with these authors, either through direct or indirect collaboration with local subject matter experts who maintain a good network with international peers.

Sensitivity maps

As mentioned in the discussion (see 2.5) the spatial data is available in varying types and is oftentimes not focused on specific impacts from energy-related activities in the context of North Sea Energy. It is recommended to use maps in the NSE Atlas that focus on the effects on species and ecosystems from

OWFs and energy islands, preferably also including cumulative effects. The included Wind Sensitivity Index on seabirds is an example of such a map. These so-called sensitivity analysis maps require an intensive effort whereby existing datasets need to be interpreted, manipulated and grouped to produce useful insights for the NSE program. Currently, an OSPAR working group (OSPR ICG-ORED) is working on developing such maps. It is recommended to seek collaboration with this program.

Legal aspects and implications

It is recommended to further look into the legal aspects and implications concerning planned activities in the NSE program, particularly with regard to the options and alternatives for different decommissioning scenarios.

Certain other knowledge gaps that are currently being included in research elsewhere and which are relevant for the NSE program to keep track off:

- Mortality and habitat displacement in relation to OWFs and seabirds and bats (WOZEP en MONS)
- Electromagnetic frequencies (Elasmopower)
- Abiotic changes and resulting habitat loss and profits (WOZEP and MONS)
- Underwater sound (WOZEP en MONS)

Structured and focused monitoring

For large-scale surveys on ecological values of structures and installations for the North Sea energy transition, a holistic and continuous risk assessment and monitoring program needs to be developed. This requires international and cross-sectoral cooperation. Due to the urgency of estimating ecological risks and values within the energy transition, it is important that research is targeted, continuous and efficient (Wilding et al., 2017). While many methods are readily available to gather data on ecological values of structures and installations in the North Sea, others are still under development but are crucial to improving research efficiency. Therefore, these projects need to be continuously supported by operators (with ROV footage and other materials), governments and NGOs (to receive proper funding) and research institutes (for expert input and peer reviews).

Also, given decision-making processes over different decommissioning scenarios (such as re-use, partial removal, or abandonment), ecological criteria need to be defined to conduct multi-criteria decision assessments (MCDAs) with an ecological focus on the future. To do so, data needs to be available on the ecological criteria chosen, hence it is recommended to develop an MCDA matrix together with knowledge institutes, NGOs and other workpackages.

The opportunities to enhance the marine ecology by leaving offshore installations and structures (partially) in place need to be weighed against potential environmental risks and adverse effects on marine ecology. This is also relevant when considering the re-use of offshore structures, for instance by transforming former O&G platforms into power to gas (P2H2) stations. More research is required on how re-use would change the ecological value of a structure since it would likely require modification or adding of submerged cables, noise and light pollution would continue (even if at reduced levels), and new activities such as the intrusion of saltwater brine into the sea. All these activities likely have a negative effect on ecology and need to be monitored carefully.

Practically, it is worth investigating the options to include ecological research and/or monitoring in periodic maintenance runs on offshore platforms.

Negative effects including cumulative effects

The potential adverse effects on the local and regional marine ecology from activities directly planned or recommended in the NSE program should be assessed. These include environmental hazards (like the output of large concentrations of brine into seawater through the production of hydrogen) or changes in hydrodynamics and sedimentation through the construction of new or alteration of existing offshore structures. This also includes a study on the effects of the construction of energy islands using sand and/or rocks, which are currently a potential design option for the energy HUBs.

In the next phase, it is recommended to further analyse the impacts of specific activities planned in the NSE program. These should include an assessment of indirect risks through cumulative effects. There should be a focus on the activities from future developments (like platform construction, operation and energy transport) and their resulting pressures and (cumulative) effects on water quality, benthos, fish and fish larvae, marine mammals, birds and bats. This includes for instance the effects on marine mammals by pile driving, the effects on birds and bats by the operation of OWF or the effects on sharks and rays by electromagnetic radiation of electrical cables. A detailed overview and comparison of activities and their effects can provide further useful insights. For this study, the results from this phase (NSE4) and those from NSE2 can be used as a baseline.

Methods to estimate ecological values

The conclusions included in this report on the feasibility of potential methods to estimate ecological values are derived from the non-exhaustive information gathered for this report, insights provided by experts and the authors' (subjective) assessment. It is recommended to further discuss and analyse the most feasible methods that best fulfil the needs of the NSE program. The upscaling of methods, future technologies and future research (e.g. on cumulative effects) should also be considered.

These assessments have not been peer-reviewed and it is recommended to determine the most preferable Hub location from a marine ecology perspective by enabling a more thorough assessment by subject matter experts through a more intensive collaboration or work sessions in the next phase of the programme.

As a final remark on estimating ecological values, some ecological values appear to differ between structures or groups of structures, based on their geographical location, depth profile, or type. This indicates that some structures and installations might be more suitable for re-using or re-purposing than others from an ecological standpoint. It also means that the ecological values provided by structures and installations could potentially be enhanced by adding structures favoured by marine species (e.g., specific scour protection structures, Glarou & Svendsen, 2020) and by considering these insights when constructing new structures and installations using nature-inclusive building techniques.

Future spatial planning within the NSE program and the NSE roadmap should be based on the information gathered from both activities conducted in this project. If the above-listed recommendations are followed, information on marine ecology could be integrated into future energy transition pathways in such a way that adverse effects on marine ecology and environmental hazards are avoided or at least minimised, while opportunities to enhance marine ecology through targeted research and improved offshore structures and installations are seized.

In any case, the results from our study have shown that more research on the impacts of offshore activities on marine ecology and more international and cross-sectoral cooperation is inevitable to achieve a sustainable energy transition.

References

Aarts, G., Brasseur, S., & Kirkwood, R. (2018). Behavioural response of grey seals to pile-driving (Report No. C006/18). Wageningen Marine Research.

Adams, T. P., Miller, R. G., Aleynik, D., & Burrows, M. T. (2014). Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. *Journal of Applied Ecology*, *51*(2), pp. 330-338.

Anand, N., Thajuddin, N., & Dadheech, P. K. (2019). Cyanobacterial taxonomy: Morphometry to molecular studies. *Cyanobacteria*, pp. 43-64. Academic Press.

Brasseur, S. M. J. M., van Polanen Petel, T., Aarts, G. M., Meesters, H. W. G., Dijkman, E. M., & Reijnders, P. J. H. (2010). *Grey seals (Halichoerus grypus) in the Dutch North sea: population ecology and effects of wind farms* (Report no. C137/10). IMARES.

Brasseur, S., G. Aarts, E. Meesters, T. V. Polanen Petel, E. Dijkman, J. Cremer & P. Reijnders. (2012). *Habitat preferences of harbour seals in the Dutch coastal area: analysis and estimate of effects of offshore wind farms* (Report no. C043/10). IMARES.

Brasseur, S. M. J. M. (2017). *Seals in motion: how movements drive population development of harbour seals and grey seals in the North Sea* [Doctoral dissertation, Wageningen University and Research]. Wageningen University.

Brevé, N. W. P., Winter, H. V., Van Overzee, H. M. J., Farrell, E. D., & Walker, P. A. (2016). Seasonal migration of the starry smooth-hound shark *Mustelus asterias* as revealed from tag-recapture data of an angler-led tagging programme. *Journal of Fish Biology*, *89*(2), pp. 1158-1177.

Capobianco, N., Basile, V., Loia, F., & Vona, R. (2021). Toward a Sustainable Decommissioning of Offshore Platforms in the Oil and Gas Industry: A PESTLE Analysis. *Sustainability*, *13*(11): 6266.

Coolen, J. W. P. (2017). *North Sea reefs: benthic biodiversity of artificial and rocky reefs in the southern North Sea* [Doctoral dissertation, Wageningen University]. Wageningen University.

Coolen, J. W., Van Der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G. W., Faasse, M. A., ... & Lindeboom, H. J. (2020). Benthic biodiversity on old platforms, young wind farms, and rocky reefs. *ICES Journal of Marine Science*, *77*(3), pp. 1250-1265.

Couton, M., Comtet, T., Le Cam, S., Corre, E., & Viard, F. (2019). Metabarcoding on planktonic larval stages: an efficient approach for detecting and investigating life cycle dynamics of benthic aliens. *Management of Biological Invasions*, *10*(4), pp. 657-689.

Dahne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krugel, K., ... & Siebert, U. (2013). Effects of pile-driving on harbour porpoises (Phocoena phocoena) at the first offshore wind farm in Germany. *Environmental Research Letters*, *8*(2), pp. 1-17.

De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., & Degraer, S. (2015). Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. *Hydrobiologia*, *756*(1), pp. 37-50.

Descôteaux, R., Ershova, E., Wangensteen, O. S., Præbel, K., Renaud, P. E., Cottier, F., & Bluhm, B. A. (2021). Meroplankton diversity, seasonality and life-history traits across the Barents Sea Polar Front revealed by high-throughput DNA barcoding. *Frontiers in Marine Science*, *8*.

Ershova, E. A., Descoteaux, R., Wangensteen, O. S., Iken, K., Hopcroft, R. R., Smoot, C., ... & Bluhm, B. A. (2019). Diversity and distribution of meroplanktonic larvae in the Pacific Arctic and connectivity with adult benthic invertebrate communities. *Frontiers in Marine Science, 6.*

Fijn, R. C., van Bemmelen, R. S. A., Arts, F. A., de Jong, J. W., Beuker, D., Rebolledo, E. B., ... & Wolf, P. A. (2020). *Verspreiding, abundantie en trends van zeevogels en zeezoogdieren op het Nederlands Continentaal Plat in 2019-2020* (Bureau Waardenburg, Report No. 20-324). RWS-Centrale Informatievoorziening BM 20.22. Bureau Waardenburg & Deltamilieu Projecten, Culemborg.

Floeter, J., van Beusekom, J. E., Auch, D., Callies, U., Carpenter, J., Dudeck, T., ... & Möllmann, C. (2017). Pelagic effects of offshore wind farm foundations in the stratified North Sea. *Progress in Oceanography*, *156*, pp. 154-173.

Fowler, A. M., Macreadie, P. I., Jones, D. O. B., & Booth, D. J. (2014). A multi-criteria decision approach to decommissioning of offshore oil and gas infrastructure. *Ocean & coastal management*, *87*, pp. 20-29.

Fowler, A. M., Jørgensen, A. M., Svendsen, J. C., Macreadie, P. I., Jones, D. O., Boon, A. R., ... & Coolen, J. W. (2018). Environmental benefits of leaving offshore infrastructure in the ocean. *Frontiers in Ecology and the Environment*, *16*(10), pp. 571-578.

Fowler, A. M., Jørgensen, A. M., Coolen, J. W., Jones, D. O., Svendsen, J. C., Brabant, R., ... & Degraer, S. (2020). The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. *ICES Journal of Marine Science*, *77*(3), pp. 1109-1126.

Garthe, S., Markones, N., & Corman, A. M. (2017). Possible impacts of offshore wind farms on seabirds: a pilot study in Northern Gannets in the southern North Sea. *Journal of Ornithology*, *158*(1), pp. 345-349.

Gass, S. E., & Roberts, J. M. (2006). The occurrence of the cold-water coral Lophelia pertusa (Scleractinia) on oil and gas platforms in the North Sea: colony growth, recruitment and environmental controls on distribution. *Marine Pollution Bulletin*, *52*(5), pp. 549-559.

Gill, A. B., Degraer, S., Lipsky, A., Mavraki, N., Methratta, E., & Brabant, R. (2020). Setting the context for offshore wind development effects on fish and fisheries. *Oceanography*, *33*(4), pp. 118-127.

Gilles, A., Viquerat, S., Becker, E. A., Forney, K. A., Geelhoed, S. C. V., Haelters, J., ... & Aarts, G. (2016). Seasonal habitat-based density models for a marine top predator, the harbor porpoise, in a dynamic environment. *Ecosphere*, *7*(6), e01367.

Hammond, P. S., Lacey, C., Gilles, A., Viquerat, S., Börjesson, P., Herr, H., . . . Øien, N. (2021). Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys. University of St. Andrews.

Heessen, Henk J.L., Niels Daan, and Jim R. Ellis (2015). *Fish Atlas of the Celtic Sea, North Sea, and Baltic Sea: Based on International Research-Vessel Surveys*. Wageningen Academic Publishers.

Henry, L. A., Mayorga-Adame, C. G., Fox, A. D., Polton, J. A., Ferris, J. S., McLellan, F., ... & Roberts, J. M. (2018). Ocean sprawl facilitates dispersal and connectivity of protected species. *Scientific reports*, *8(1): 11346*.

IEA (2021), *Net Zero by 2050*, IEA, Paris https://www.iea.org/reports/net-zero-by-2050

Kesselring, T., Viquerat, S., Brehm, R., & Siebert, U. (2017). Coming of age: - Do female harbour porpoises (Phocoena phocoena) from the North Sea and Baltic Sea have sufficient time to reproduce in a human influenced environment?. PloS one, 12(10), e0186951. https://doi.org/10.1371/journal.pone.0186951

Lagerveld, S., van der Wal, J. T., Vries, V., Verdaat, H., Sonneveld, C., van der Meer, J., ... & Noort, B. (2019). *Bats at the southern North Sea in 2017 & 2018* (Report No. C062/19). Wageningen Marine Research.

Leopold, M. F., Boonman, M., Collier, M. P., Davaasuren, N., Jongbloed, R. H., Lagerveld, S., ... & Scholl, M. M. (2014). *A first approach to deal with cumulative effects on birds and bats of offshore wind farms and other human activities in the Southern North Sea* (Report No. C166/14). IMARES.

Leopold, M. F., & van der Wal, J. T. (2021). Windmolengevoeligheidskaart Noordzee: update 2021 (Report no. C104/21). Wageningen Marine Research.

Lindeboom, H. J., Dijkman, E. M., Bos, O. G., Meesters, H. W. G., Cremer, J. S. M., Raad, de I., & Bosma, A. (2008). *Ecologische Atlas Noordzee ten behoeve van gebiedsbescherming* [2e dr.]. Wageningen Imares.

Martins, I. D., Moraes, F. F., Távora, G., Soares, H. L. F., Infante, C. E., Arruda, E. F., ... & Lourenço, M. I. (2020). A review of the multicriteria decision analysis applied to oil and gas decommissioning problems. *Ocean & Coastal Management*, *184: 105000*.

Mercator Ocean International (2021). Atlantic - European North West Shelf - Ocean Biogeochemistry Analysis and Forecast. Mercator Ocean International. https://doi.org/10.48670/moi-00056

Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Synthesis* (pp. 39-48). Island Press, Washington, DC.

Parzanini, C., Parrish, C. C., Hamel, J. F., & Mercier, A. (2018). Trophic relationships of deep-sea benthic invertebrates on a continental margin in the NW Atlantic inferred by stable isotope, elemental, and fatty acid composition. *Progress in Oceanography*, *168*, pp. 279-295.

Peschko, V., Ronnenberg, K., Siebert, U., & Gilles, A. (2016). Trends of harbour porpoise (Phocoena phocoena) density in the southern North Sea. *Ecological Indicators*, *60*, pp. 174-183.

Pint, S., De Troch, M., Oevelen, D., Heymans, J., Everaert, G. (2021). Ecopath model of the southern North Sea. 10.13140/RG.2.2.28319.07844.

Reubens, J. T., Braeckman, U., Vanaverbeke, J., Van Colen, C., Degraer, S., & Vincx, M. (2013). Aggregation at windmill artificial reefs: CPUE of Atlantic cod (Gadus morhua) and pouting (Trisopterus luscus) at different habitats in the Belgian part of the North Sea. *Fisheries Research*, *139*, pp. 28-34.

Rouse, S., Lacey, N. C., Hayes, P., & Wilding, T. A. (2019). Benthic conservation features and species associated with subsea pipelines: considerations for decommissioning. *Frontiers in Marine Science*, *6: 200*.

Russell, D. J., Hastie, G. D., Thompson, D., Janik, V. M., Hammond, P. S., Scott-Hayward, L. A., ... & McConnell, B. J. (2016). Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology, 53(6), pp. 1642-1652.

Schutter, M., Dorenbosch, M., Driessen, F. M., Lengkeek, W., Bos, O. G., & Coolen, J. W. (2019). Oil and gas platforms as artificial substrates for epibenthic North Sea fauna: Effects of location and depth. *Journal of Sea Research*, *153: 101782*.

Sguotti, C., Lynam, C. P., García-Carreras, B., Ellis, J. R., & Engelhard, G. H. (2016). Distribution of skates and sharks in the North Sea: 112 years of change. *Global change biology*, *22*(8), pp. 2729-2743.

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), pp. 35-53.

Sommer, B., Fowler, A. M., Macreadie, P. I., Palandro, D. A., Aziz, A. C., & Booth, D. J. (2019). Decommissioning of offshore oil and gas structures–Environmental opportunities and challenges. *Science of the total environment*, *658*, pp. 973-981.

Stalder, D., van Beest, F. M., Sveegaard, S., Dietz, R., Teilmann, J., & Nabe-Nielsen, J. (2020). Influence of environmental variability on harbour porpoise movement. *Marine Ecology Progress Series*, *648*, pp. 207-219.

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., & Carlier, A. (2018). A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews, 96, pp.* 380-391.
mole

Thorpe, S. A. (2012). On the biological connectivity of oil and gas platforms in the North Sea. *Marine pollution bulletin*, *64(12)*, pp. 2770-2781.

Todd, V. L., Lazar, L., Williamson, L. D., Peters, I. T., Hoover, A. L., Cox, S. E., ... & McLean, D. L. (2020). Underwater visual records of marine megafauna around offshore anthropogenic structures. *Frontiers in Marine Science*, *7: 230*.

Van der Molen, J., 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*.

van der Wal, J. T., Quirijns, F. J., Leopold, M. F., Slijkerman, D. M. E., Glorius, S. T., & Jongbloed, R. H. (2011). *Inventory of current and future presence of non-wind sea use functions second edition* (Report no. C036/11). IMARES.

van Duren, L.A., Zijl, F., van Kessel, T., van Zelst, V.T.M., Vilmin, L.M., van der Meer, J., … & Minns, A.W. (2021). *Ecosystem effects of large upscaling of offshore wind on the North Sea - Synthesis report (22 April 2021).* Deltares.

Verbeek, S., Jørgensen, A.-M. & Pors, J. (2018). *Worldwide Rigs-to-Reefs Experiences: Considerations and Motivation for a Living North Sea.* (Report Feasibility Update, Living North Sea Initiative, Report No. LNSF250_D02). IMSA Amsterdam.

Waggitt, J. J., Evans, P. G., Andrade, J., Banks, A. N., Boisseau, O., Bolton, M., ... & Hiddink, J. G. (2020). Distribution maps of cetacean and seabird populations in the North‐East Atlantic. *Journal of Applied Ecology*, *57*(2), pp. 253-269.

Webb, K. E., Barnes, D. K., Clark, M. S., & Bowden, D. A. (2006). DNA barcoding: a molecular tool to identify Antarctic marine larvae. *Deep Sea Research Part II: Topical Studies in Oceanography*, *53*(8-10), pp. 1053-1060.

Wright, S. R., Lynam, C. P., Righton, D. A., Metcalfe, J., Hunter, E., Riley, A., ... & Hyder, K. (2020). Structure in a sea of sand: fish abundance in relation to man-made structures in the North Sea. *ICES Journal of Marine Science*, *77*(3), pp. 1206-1218.

Annexes

Annex 1: Expert consultations

Expert Consultations Conducted for Activity 2

Contact Person	Organisation/ Company	Type of communication	Subject	Date
Renate Olie and Heleen Vollers	Stichting De Nordzee	Peer review	Ecological layers for the NSE Atlas	Received 15.12.2021
Marjolein Kelder	De Rijke Nordzee	Peer review	Ecological layers for the NSE Atlas	Received 15.12.2021
Peter De Jong	Natuur & Milieu	Peer review	Ecological layers for the NSE Atlas	Received 15.12.2021
Britta Schaffmeister	Dutch Marine Energy Center	Peer review	Ecological layers for the NSE Atlas	Received 08.12.2021
Sophie de Reus	RHDHV	Peer review	Ecological layers for the NSE Atlas	Received 02.12.2021
Dr. Joop Coolen	WMR	Interview	Epibenthic growth sampling methods and visual species identification using ROV materials	13.01.2022
John Halpin, Dr. Tom Wilding, Dr. Joseph Marlow	NS3D-NERC (SAMS)	Meeting	Automatic species identification and 3D modelling of benthos using ROV materials	13.12.2021
Anne-Mette Jörgensen	NSE, Eco-Effective Strategies, INSITE	Meeting	Recent research and knowledge gaps of assessing ecological value of offshore structures. Implementation and stakeholders.	17.01.2022
Lisa van Nieuwkoop	NSE	E-Mail, Meeting	Changing policy in decommissioning, conservation policy, legal challenges and opportunities	Received 25.01.2022 Meeting 04.02.2022
Ruben Fijn	BuWa	E-Mail	Monitoring bird movement and behaviour on and close to offshore structures	Received 26.01.2022

Annex 2: Spatial data inventory

Inventory of reviewed published spatial data in literature for the ecological layers of the NSE Atlas

Goup	Species	Literature Item
PP		van Duren, L.A., Zijl, F., van Kessel, T., van Zelst, V.T.M., Vilmin, L.M., van der Meer, J., … & Minns, A.W. (2021). *Ecosystem effects of large upscaling of offshore wind on the North Sea - Synthesis report (22 April 2021).* Deltares.
Benthos		Bos, O. G., Witbaard, R., Lavaleye, M. S. S., Moorsel, G. W. N. M., Teal, L. R., Van Hal, R., … & Dijkman, E. M. (2011). *Biodiversity hotspots on the Dutch Continental Shelf: a marine strategy framework directive perspective* (Report no. C071/11). IMARES.
		Jongbloed, R. H., van der Wal, J. T., & Lindeboom, H. J. (2014). Identifying space for offshore wind energy in the North Sea. Consequences of scenario calculations for interactions with other marine uses. *Energy Policy*, *68*, pp. 320-333.
		Lindeboom, H. J., Dijkman, E. M., Bos, O. G., Meesters, H. W. G., Cremer, J. S. M., Raad, de I., & Bosma, A. (2008). *Ecologische Atlas Noordzee ten behoeve van gebiedsbescherming* [2e dr.]. Wageningen Imares. .
		van der Wal, J. T., Quirijns, F. J., Leopold, M. F., Slijkerman, D. M. E., Glorius, S. T., & Jongbloed, R. H. (2011). *Inventory of current and future presence of non-wind sea use functions second edition* (Report no. C036/11). IMARES
		Verduin, E.C. ,Olie, R., Faasse, M.A., van Deelen, J.J. (2020). *Macrozoöbenthosonderzoek met de bodemschaaf op de Noordzee - Rapportage 2019* (Report no. 03/2020). Eurofins AquaSense. Rijkswaterstaat, Centrale Informatie Voorziening (RWS-CIV).
Cetaceans	Harbour porpoise	Geelhoed, S. C. V., Scheidat, M., & Van Bemmelen, R. S. A. (2013). *Marine mammal surveys in Dutch waters in 2012* (Report no. C038/13). IMARES.
		Geelhoed, S. C., & Scheidat, M. (2018). Abundance of harbour porpoises (Phocoena phocoena) on the Dutch Continental Shelf, aerial surveys 2012-2017. *Lutra*, *61*, pp. 127-136
		Geelhoed, S. C., Janinhoff, N., Lagerveld, S., & Verdaat, H. (2020). *Marine mammal surveys in Dutch North Sea waters in 2019* (Report no. C016/20). Wageningen Marine Research.
		Gilles, A., Viquerat, S., Becker, E. A., Forney, K. A., Geelhoed, S. C. V., Haelters, J., … & Aarts, G. (2016). Seasonal habitat-based density models for a marine top predator, the harbor porpoise, in a dynamic environment. *Ecosphere, 7(6), e01367*
		Hammond, P. S., Macleod, K., Berggren, P., Borchers, D. L., Burt, L., Cañadas, A., … & Vázquez, J. A. (2013). Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. *Biological Conservation*, *164*, pp. 107-122
		Hammond, P. S., Lacey, C., Gilles, A., Viquerat, S., Boerjesson, P., Herr, H., … & Øien, N. (2017). *Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys*. Wageningen Marine Research.
		Scheidat, M., Verdaat, H., & Aarts, G. (2012). Using aerial surveys to estimate density and distribution of harbour porpoises in Dutch waters. *Journal of Sea Research*, *69*, pp. 1–7.
		von Benda-Beckmann, S., Geelhoed, S. C. V., Kinneging, N., van Kuijk, B., Scheidat, M., & Versteeg, S. (2020). *Assessment methodology for impulse noise: A case study on three species in the North Sea* (Report No. D100147). Arcadis.
		Waggitt, J. J., Evans, P. G., Andrade, J., Banks, A. N., Boisseau, O., Bolton, M., … & Hiddink, J. G. (2020). Distribution maps of cetacean and seabird populations in the North-East Atlantic. *Journal of Applied Ecology*, *57(2)*, pp. 253-269.
	Others	Geelhoed, S. C. V., Scheidat, M., & Van Bemmelen, R. S. A. (2013). *Marine mammal surveys in Dutch waters in 2012* (Report no. C038/13). IMARES.
		Hammond, P. S., Macleod, K., Berggren, P., Borchers, D. L., Burt, L., Cañadas, A., … & Vázquez, J. A. (2013). Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. *Biological Conservation*, *164*, pp. 107-122.
		Hammond, P. S., Lacey, C., Gilles, A., Viquerat, S., Boerjesson, P., Herr, H., … & Øien, N. (2017). *Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys*. Wageningen Marine Research.

		Reid, J. B., Evans, P. G., & Northridge, S. P. (Eds.). (2003). *Atlas of cetacean distribution in north-west European waters*. Joint Nature Conservation Committee.
		Waggitt, J. J., Evans, P. G., Andrade, J., Banks, A. N., Boisseau, O., Bolton, M., ... & Hiddink, J. G. (2020). Distribution maps of cetacean and seabird populations in the North-East Atlantic. *Journal of Applied Ecology*, *57(2)*, pp. 253-269.
Fish	Fish	Heessen, Henk J.L., Niels Daan, and Jim R. Ellis (2015). *Fish Atlas of the Celtic Sea, North Sea, and Baltic Sea: Based on International Research-Vessel Surveys*. Wageningen Academic Publishers.
		ICES. 2021. Working Group on Marine Mammal Ecology (WGMME). ICES Scientific Reports. 3:19. 155 pp. https://doi.org/10.17895/ices.pub.8141
		Van der Wal, J. T., Quirijns, F. J., Leopold, M. F., Slijkerman, D. M. E., & Jongbloed, R. H. (2011). *Calculation rules for the DSS* (Report no. C010/11). IMARES.
	Elasmobranchs	ICES. 2021. Working Group on Marine Mammal Ecology (WGMME). ICES Scientific Reports. 3:19. 155 pp. https://doi.org/10.17895/ices.pub.8141
		Sguotti, C., Lynam, C. P., García-Carreras, B., Ellis, J. R., & Engelhard, G. H. (2016). Distribution of skates and sharks in the North Sea: 112 years of change. *Global change biology*, *22*(8), pp. 2729-2743.
Seals	Harbor Seal	Aarts, G. M., Brasseur, S. M. J. M., Geelhoed, S. C. V., van Bemmelen, R. S. A., & Leopold, M. F. (2013). *Grey and harbour seal spatiotemporal distribution along the Dutch West coast* (Report no. C103/13). IMARES.
		Brasseur, S., G. Aarts, E. Meesters, T. V. Polanen Petel, E. Dijkman, J. Cremer & P. Reijnders. (2012). *Habitat preferences of harbour seals in the Dutch coastal area: analysis and estimate of effects of offshore wind farms* (Report no. C043/10). IMARES.
		Brasseur, S. M., & Kirkwood, R. J. (2015). *Seal monitoring and evaluation for the Gemini offshore windpark: Pre-construction, T0-2014 report* (Report no. C128/14). IMARES.
		Kirkwood, R. J., Aarts, G. M., & Brasseur, S. M. (2015). *Seal monitoring and evaluation for the Luchterduinen offshore wind farm: 2. Tconstruction-2014 report* (Report no. C152/14). IMARES.
	Grey Seal	Aarts, G. M., Brasseur, S. M. J. M., Geelhoed, S. C. V., van Bemmelen, R. S. A., & Leopold, M. F. (2013). *Grey and harbour seal spatiotemporal distribution along the Dutch West coast* (Report no. C103/13). IMARES.
		Brasseur, S. M. J. M., van Polanen Petel, T., Aarts, G. M., Meesters, H. W. G., Dijkman, E. M., & Reijnders, P. J. H. (2010). *Grey seals (Halichoerus grypus) in the Dutch North sea: population ecology and effects of wind farms* (Report no. C137/10). IMARES.
		Brasseur, S. M. J. M. (2017). *Seals in motion: how movements drive population development of harbour seals and grey seals in the North Sea* [Doctoral dissertation, Wageningen University and Research]. Wageningen University.
		Brasseur, S., Kirkwood, R., & Aarts, G. (2018). *Seal monitoring and evaluation for the Gemini offshore windfarm: Tconstruction-2015 report* (Report no. C004/18). Wageningen Marine Research.
		Kirkwood, R. J., Aarts, G. M., & Brasseur, S. M. (2015). *Seal monitoring and evaluation for the Luchterduinen offshore wind farm: 2. Tconstruction-2014 report* (Report no. C152/14). IMARES.
		Peschko, V., Müller, S., Schwemmer, P., Mercker, M., Lienau, P., Rosenberger, T., ... & Garthe, S. (2020). Wide dispersal of recently weaned grey seal pups in the Southern North Sea. *ICES Journal of Marine Science*, *77*(5), pp. 1762-1771.
Birds		Bos, O. G., Witbaard, R., Lavaleye, M. S. S., Moorsel, G. W. N. M., Teal, L. R., Van Hal, R., ... & Dijkman, E. M. (2011). *Biodiversity hotspots on the Dutch Continental Shelf: a marine strategy framework directive perspective* (Report no. C071/11). IMARES.
		Fijn, R. C., van Bemmelen, R. S. A., Arts, F. A., de Jong, J. W., Beuker, D., Rebolledo, E. B., ... & Wolf, P. A. (2020). *Verspreiding, abundantie en trends van zeevogels en zeezoogdieren op het Nederlands Continentaal Plat in 2019-2020* (Bureau Waardenburg, Report No. 20-324). RWS-Centrale Informatievoorziening BM 20.22. Bureau Waardenburg & Deltamilieu Projecten, Culemborg.
		Jongbloed, R. H., van der Wal, J. T., & Lindeboom, H. J. (2014). Identifying space for offshore wind energy in the North Sea. Consequences of scenario calculations for interactions with other marine uses. *Energy Policy*, *68*, pp. 320-333.
		Leopold, M. F., & Dijkman, E. M. (2010). *Offshore wind farms and seabirds in the Dutch Sector of the North Sea* (Report no. C134/10). IMARES.

		Leopold, M. F., Boonman, M., Collier, M. P., Davaasuren, N., Jongbloed, R. H., Lagerveld, S., ... & Scholl, M. M. (2014). *A first approach to deal with cumulative effects on birds and bats of offshore wind farms and other human activities in the Southern North Sea* (Report No. C166/14). IMARES.
		Leopold, M. F. (2017). *Seabirds?: what seabirds?: An exploratory study into the origin of seabirds visiting the SE North Sea and their survival bottlenecks* (Report no. C046/17). Wageningen Marine Research.
Bats	Nauthusius pipistrelle	Boshamer, J. P., & Bekker, J. P. (2008). Nathusius' pipistrelles (Pipistrellus nathusii) and other species of bats on offshore platforms in the Dutch sector of the North Sea. *Lutra*, *51*(1), pp. 17-36.
		Lagerveld, S., Poerink, B. J., Haselager, R., & Verdaat, H. (2014). Bats in Dutch offshore wind farms in autumn 2012. *Lutra*, *57*(2), pp. 61-69.
		Lagerveld, S., Poerink, B. J., & Verdaat, J. P. (2014). *Monitoring bat activity in offshore wind farms OWEZ and PAWP in 2013* (Report no. C165/14). IMARES.
		Lagerveld, S., van der Wal, J. T., Vries, V., Verdaat, H., Sonneveld, C., van der Meer, J., ... & Noort, B. (2019). *Bats at the southern North Sea in 2017 & 2018* (Report No. C062/19). Wageningen Marine Research.
		Leopold, M. F., Boonman, M., Collier, M. P., Davaasuren, N., Jongbloed, R. H., Lagerveld, S., ... & Scholl, M. M. (2014). *A first approach to deal with cumulative effects on birds and bats of offshore wind farms and other human activities in the Southern North Sea* (Report No. C166/14). IMARES.

Inventory of relevant open-source layers assessed for the ecological layers for the NSE Atlas

Group	Open Layer Service	Data Item	Data Referencing
Bathymetry	EMODnet Bathymetry Viewing and Download service	2020 Mean depth rainbow colour ramp (no land data)	
	GEBCO	2021 Gridded Bathymetry Data	
PP	Copernicus	NWSHELF_ANALYSISFORECAST_BGC_004_002	https://doi.org/10.48670/moi-00056
Benthos	WMR GeoServer	WMRwms:NZ2030_Schaaf_SpecRich	
	WMR GeoServer	WMRwms:NZ2030_BioMon_SpecRich	
	RWS Waterinfo Extra	Benthos DONAR 1978-2007	
	RWS Waterinfo Extra	Benthos Nordzee	
	Informatiehuis Marien	IHM OpenData Wageningen Marine Research (IMARES): Schelpdieren CSO WOT 1993-2009	
Cetaceans	DRYAD	Waggitt, James (2019), Data from: Distribution maps of cetacean and seabird populations in the North-East Atlantic, Dryad, Dataset	https://doi.org/10.5061/dryad.mw6m905sz
	EMODnet Biology	Gridded abundance maps of marine mammals from the North Sea	
	OBIS-SEAMAP		

Annex 3: Methods in comparison

In Table 1, an overview is provided of the most relevant methods and how they compare in (i) measuring abiotic and biotic data (ii) availability and applicability to different structure types and (iii) cost/ time efficiency. The biotic parameters refer to the species sampled by the respective methods (epibenthic species or fish/mammals or larvae). Methods are compared of the same scale may be compared.

Symbol	--	-	+/-	+	++	?
Performance	very poor	poor	medium/ case-dependent	high	very high	unknown/ not reviewed

Table 1: Methods in Comparison

		Epifouling Communities			Fish and Marine Mammals			Larvae Streams (Connectivity)	
		Sampling (divers)	ROV Observations	ROV Auto ID/ 3D	IBTS Analysis (fish only)	Tagging	Observations	Sampling	Prediction Model
Biotic Data	Species Absence/ Presence	++	+	+	+/-	--	++	+/-	++
	Species Richness	++	+	+	+/-	--	+	+/-	+
	Abundance	++	+	+	+	--	+	+/-	+
	Biomass/ Weight	++	--	+	+/-	--	-	--	--
	Behaviour	+/-	?	--	-	+	++		
Abiotic Data	Geographical Location	+	++	++	++	++	+/-	+	++
	Depth	++	++	++	?	+	+/-	-	+
	Environmental Data	?	?	?	--	+	-	+	
	Structure Characteristics	++	+	-	--	--	+	+	
Availability	Method Available	++	++	+/-	++	++	++	++	+/-
	Data (Results) Available	+	++	+/-	++	+	+	?	+/-
	Tested	++	++	+	++	++	++	++	+
	Standardised	--	-	-	+	+	-	-	--
Applicability	Useable on O&G	++	++	++	+/-	++	++	++	++
	Useable on OWF	++	?	?	+/-	++	++	++	++
	Useable, others (pipes, H2G)	++	?	?	+/-	++	+/-	+/-	?
Efficiency	Costs	--	++	?	++	+	++	+	?
	Time	-	+	?	+	+	+/-	+	+/-

In collaboration and appreciation to

TNO
New Energy Coalition
Rijksuniversiteit Groningen
Royal HaskoningDHV
NEN
Energieke Communicatie
MSG
TKI Nieuw Gas
Total Energies
Shell
NAM
EBN
Gasterra
Gasunie
ONE-Dyas
Bilfinger Tebodin
DEME Offshore NL
Boskalis
Neptune Energy
IV Offshore & Energy
Bureau Veritas
HINT Europe
NGT
NOGAT
Peterson Energy
Port of Den Helder
Port of Amsterdam
Port of Rotterdam
SmartPort
Element NL
Equinor Energy
Net Zero Technology Centre

Sounding board

Dutch Marine Energy Centre
Ministerie Economische Zaken & Klimaat
IRO
Stichting Natuur & Milieu
Nexstep
Stichting Noordzee
NWEA
Tennet
TKI Wind op Zee
Visned
Rijkswaterstaat
Topsector Energie
BOZ

North Sea Energy
offshore system integration