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Research Project

Nature inclusivity in offshore wind farms

A framework of existing, upcoming and missing solutions to implement in offshore wind farm design and planning for the protection and enhancement of marine ecosystems; And a case study of a nature inclusive scour protection solution in offshore wind farm Hollandse Kust Zuid.

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Nature-inclusivity in offshore wind farms: A framework of existing, upcoming and missing solutions to implement in offshore wind farm design and planning for the protection and enhancement of marine ecosystems; And a case study of a nature inclusive scour protection solution in offshore wind farm Hollandse Kust Zuid.

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Key words: Offshore wind farms, nature inclusivity, nature protection, nature restoration, ecological impact, ecological mitigation.

Abstract

The large-scale development of Offshore Wind Farms (OWFs) is on a trajectory to change the ecology of European waters, such as the North Sea. This will cause harm to its marine ecosystem, including collision, disturbance, displacement, entanglement and habitat loss for avian species, marine fauna and benthos. Simultaneously, OWFs offer major restoration potential for marine ecosystems. Naturally OWFs resemble sanctuaries for fish and benthos due to reduced fishing pressure and availability of hard substrate. This consequently instigates knock-on ecosystem functioning effects like increased food availability and fish stocks. This study offers a comprehensive framework of the mitigation and nature enhancement solutions that can be implemented in the design and planning of an OWF to mitigate its negative ecological impacts and enhance the positives. Touching on both infrastructural design options and planning considerations, a wide palette of nature inclusivity solutions is presented and evaluated in terms of deployability and mitigation effectiveness. The results reveal that many on-market solutions, such as noise reduction techniques during pile driving, bird collision avoidance measures and systems, and artificial reef structures, minimise but do not avoid all ecological impacts of OWFs. The most effective solutions are those that avoid an ecological impact in the first place, instead of minimising or restoring it. Currently this includes siting, routing and micrositing around valuable habitat and planning around sensitive periods, such as breeding, spawning and migration seasons. A promising technology is that of *jetting* monopile foundations to silently install them, which is more effective than emerging solutions that absorb and minimise sound pollution. Importantly, to effectively restore marine habitat, artificial reefs should be designed into the base case of an OWF instead of as standalone structures. Integrating heterogeneous calcareous rocks into scour protection represents the most cost-effective and scalable habitat restoration solution. Nevertheless, many existing and upcoming solutions that have gained popularity consist of heavily processed small-scale artificial reef structures. Additionally, this study considers adaptations required to nature inclusive solutions to suit future trends in offshore renewables. Floating turbine technology and the growing competition over ocean space, both pose new ecological risks as well as opportunities. Co-location with offshore hydrogen is a blind spot for nature protection and enhancement efforts within OWFs. As well, the long-term deployment and large-scale expansion of OWFs in the marine space form unresolved ecological uncertainties, which urgently require further research. Overall, this research underscores that there is a discrepancy between nature inclusive innovations being developed and ecological impacts that most urgently need addressing. Complementing the knowledge framework on nature inclusivity in OWFs, is a case study of a nature inclusive scour protection solution deployed in OWF Hollandse Kust Zuid (HKZ). This proof-of-principle study evaluates the suitability of marine ecological monitoring with an Remotely Operated Vehicle (ROV) on substrates prevailing in HKZ. It provides a valuable initial insight into the benthic and pelagic species present in this novel North Sea habitat. No statistically significant differences were found between the species composition of scour protection, reef, cable and sand substrate. However, the preliminary results appear to suggest that adding boulders of various sizes on top of conventional scour protection, could serve as suitable habitat for target species *Gadus morhua*.

1. Introduction

1.1 The trajectory of offshore wind energy

Offshore Wind Farms (OWFs) are amongst the most suitable form of electricity production of today and tomorrow. With governmental bodies, such as the European Union, striving to reduce greenhouse-gas emissions and accomplish climate neutrality (European Commission, 2021), the transition from fossil fuels to renewable energy is in full swing. In executing a successful energy transition, many European and South Asian countries have embraced offshore wind. This is due to its high technical potential, high energy output and huge cost reduction potential (Williams and Zhao, 2023). As of 2022, Chen and Su (2022) report that OWFs have been installed in European waters in the UK (n = 30), Germany (n = 19), Denmark (n = 13), the Netherlands (n = 6), Belgium (n = 6), and Sweden (n = 4) and in Asia mainly in China (n = 21), Japan (n = 4), South Korea (n = 2), Taiwan (n =2), and Vietnam (n =1), where the USA (n=1) is the only country in the Americas with an operational OWF (Díaz and Guedes Soares, 2020). Having the world's largest

and most competitive wind supply chain, China is prospected to add 15 GW of the global total of 60GW that will be newly installed between 2023 and 2032 (Williams and Zhao, 2023). European installations are prospected to add 29.5 GW in the same time and by 2050 even multiply by five-fold compared to 2023 (Pettersen et al., 2023). Varying advancements in OWF development are also made in East Coast America, the Mediterranean Sea, India, Australia, New Zealand, Brasil, Colombia and South Africa with policy targets and auctions set, sites allocated and a few constructions underway (4C Offshore, 2024). In the present-day context of supply-side constraints and high energy prices, underlying geopolitics stimulate nations desire to become self-reliant in their energy provision (Galparsoro et al., 2022). Consequently, OWF development is on a trajectory to conquer shallow and deep waters across the globe.

An OWF consists of multi-megawatt wind turbines with a recommended maximum tip height of 305 meter (Pondera, 2024). Between turbines, inter-array cables are placed to channel the generated energy, to a central point within the OWF. This is the substation. The substation houses the electrical high-voltage and medium-voltage components for transforming power and connects to an export cable which transfer electricity to the onshore grid (Ørsted, 2023). Each turbine compromises of a nacelle, rotor, three blades and a tower above water (Bennun et al., 2021). The structure of the tower below the water surface is the turbine's foundation. There are a number of different types of foundations, however the most common are fixed-bottom foundations of the monopile and jacket type (see figure 1). These respectively make up 69% and 20% of all installed turbine foundations in 2011 (Wilkes et al., 2012). Fixed-bottom turbine foundations and any cabling is covered in scour protection. Scour protection consists of layers of rock material, such as granite or concrete, to withstand park infrastructure from seabed erosion (Glarou et al., 2020). At present, most OWFs are located in shallow waters with a maximum depth of 20 meters on glacial and marine deposits of sand (Stenberg et al., 2015), and thus the majority contains monopile foundations.

With the 2017 opening of the first prototype floating wind park of Hywind in Scotland, a new era of OWF development commenced (Azcona et al., 2019). Floating turbines, unlike fixed-bottom turbines, balance on a floater attached to the seafloor by moorings and anchoring systems (Lloret et al. 2023). This grants them access to deeper waters and thus more ocean surface space (SEER, 2022).

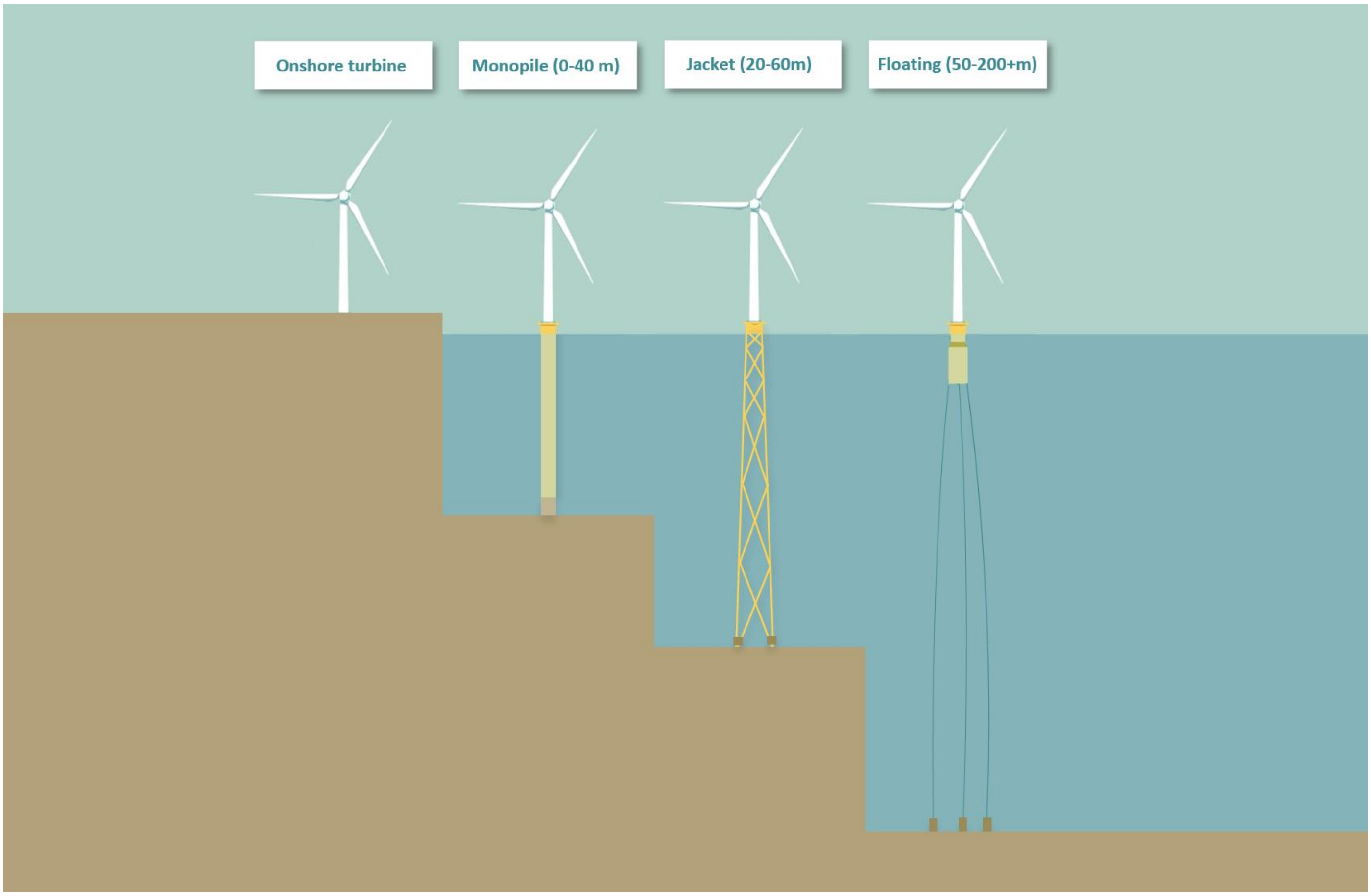


Figure 1. An overview of the different types of wind turbine foundations and their respective depth limits, as currently technologically possible for the construction of offshore wind farms (References: Turbine type and depth information (Keene, 2021). Graphic elements adjusted in Microsoft PowerPoint (Nord-Lock Group, 2025).

1.2 Ecological impacts of OWFs

The development, operation and eventual disassembly of OWFs have positive and negative impacts on the marine environment (Belu et al., 2017). On an oceanographic scale, the most obvious benefit of OWFs is that offer an alternative to oil, gas and coal. These finite sources of energy contribute to ocean warming, oxygen depletion and acidification, accounting for up to half of the combined impacts of climate change on ecological decline (European Environment Agency, 2023). The energy required and associated CO_2 emitted throughout the life-cycle of an OWFs is returned after 6 to 12 months of operation (National Renewable Energy Laboratory, 2011). Besides emission-free energy generation, OWFs provide additional ecological enhancements to the marine environment (Renewables Grid Initiative, 2024). These include habitat creation on the OWF infrastructure and protection from harmful fishing practices, with associated spillover effects into neighbouring areas (Firestone and Kempton, 2007). Collision, disturbance, displacement, entanglement and habitat loss are among the range of negative ecological impacts, although the extent of these impacts varies significantly throughout the life cycle of an OWF (Jhan et al., 2022).

With considerate design, OWFs not only mitigate climate change by producing emission-free energy, they also have the potential to enhance local biodiversity (Werner et al., 2024). Predominantly situated on the uncovered soft-bottom habitat of sand (Coolen et al., 2018), the scour protection naturally introduces new hard substrate into the environment (Leander Vølstad et al., 2022). It provides suitable settlement conditions for biogenic reef-builders, such as like the native oyster and the blue mussel in the North Sea (Dunkley and Solandt, 2022). There is resemblance between an artificial reef and scour protection (Schutter et al., 2019). The former is a submerged hard substrate mimicking a natural reef, deliberately placed on the seabed for this purpose. The later, embodies the same characteristics yet as an unintentional bonus of renewable energy production at sea. In the absence of bottom towed fishing devices, microorganisms colonise, attracting benthic species such as crabs and starfish who feed on them. And in turn the larger predators, such as cod, gravitate to these environments too (Leander Vølstad et al., 2022).

In potential OWFs can function as restored bivalve reefs (Ter Horstede et al., 2024), which were historically plentiful in temperate waters like the southern North Sea (Olsen, 1883). These have degraded to the point of ecosystem collapse after decades of industrial trawling and overharvesting (Coolen, 2017). Due to safety concerns, OWF developers gain exclusive access to large areas of sea for their park infrastructure, excluding other maritime uses, such as commercial fisheries (Schupp et al., 2021). This creates a natural exclusion zone from fishing pressure (Dunkley and Solandt, 2022), which is known as the *reserve effect.* Reduced fishing pressures around OWFs generate increased biodiversity and abundance from many benthic and fish taxa, even porpoises as long as gillnet fishing is prohibited (Hammar et al., 2016). Similar to the protective mechanism of a Marine Protected Area (MPA), enforcing a no-take zone around OWF infrastructure, increases the abundance and occurrence of ecologically and economically important species (Pardo et al., 2023). Halouani et al. (2020) suggests that the spillover effect into surrounding fishing grounds could mitigate for the fishery restrictions (loss of access) in OWF, by increasing the proportion of high trophic level species.

The physical and chemical disruptions of turbine placement, during construction, and removal, during disassembly, impact not only primary production patterns but also smother microorganisms. This disrupts suspension feeders and those organisms that feed on them (Degraer et al., 2020). Consequently, OWFs cause, to varying extents temporary or permanent, harm all up and down the food web (Bennun et al., 2021). This harm includes displacement, behavioural changes, injury and mortality to benthic and pelagic organisms. The installation of offshore wind turbines constitutes of approximately 0.8% of the total area of an OWF (Glarou et al., 2020). The soft-bottom habitat lost with their installation and the associated loss of biological abundance is insignificant at population scale (van Hal et al., 2017). Hence, there is increasing evidence to suggest that through appropriate siting and management, OWFs can have a net positive impact on the marine environment (Jhan et al., 2022).

1.3 Nature inclusivity in OWF design, planning and operation

A range of disciplines, including agriculture, urban planning, civil engineering and water management, have come to embrace nature inclusivity. These include design movements like Nature Inclusive Design (NID), Building with Nature and Nature Based Solutions (NBS). The latter can be defined as any actions to protect, conserve, restore, sustainably use and mange natural or modified ecosystems (IUCN, ILO, & UNEP, 2022) whilst providing environmental, social and economic benefits and resilience (Alva, 2022). Nature-inclusivity proposes a means of ingenuity that considers both human interests and those of the natural environment, which sometimes creates the opportunity for nature to do some of the work (Van Stiphout, 2021). Within the realm of OWFs, Hermans et al., 2020 have defined NID as *'options that can be integrated in or added to the design of an offshore wind infrastructure to create suitable habitat for native species (or communities) whose natural habitat in the Dutch North Sea has been degraded or reduced'*. This includes a focus on vulnerable autochthonous species and habitat types which have been regulatory designated to prioritise in protection or don't have a favourable conservation status yet (Hermans et al., 2020). By targeting umbrella species, habitat is expected to be optimised for a wider range of native biodiversity (Lengkeek et al., 2017).

In selecting new OWF locations to tender for development, policy makers consider existing spatial claims over sea space. As well as environmental parameters, public concerns and techno-economic criteria like water depth, wind speed cost and subsidies (Ruijgrok et al., 2019). A novel addition to tender criteria for OWFs is the incorporation of nature-inclusive construction and nature enhancement efforts (Rijksoverheid, 2022 in Kingma et al, 2024). The Dutch Ministry of Agriculture, Nature and Food Quality is the global forerunner of operationalising such permit obligations, steering OWF design in the Dutch North Sea toward ecosystem strengthening (Min I&M and Min EZ, 2014 in Bos et al., 2023). Particularly, by focussing on enhancement of ecological functioning of policy-relevant marine species, such as the Atlantic cod and European flat oyster, that naturally occur in the Netherlands (Hermans et al., 2020). Integrating nature-inclusive features into the OWF design, wind energy generation at sea can serve as a rehabilitation vehicle of the degraded North Sea habitat (The North Sea Foundation, 2022).

By creating value for local key species, endangered species or species of commercial value, nature inclusivity measures in OWF areas can serve as means to restore degraded habitats, enhance ecological functioning and promote biological production and diversity (DNV and NIVA, 2023). With the hard substrate of the park infrastructure providing settlement conditions and shelter for sea life, OWFs can be a catalyst for nature (van Duren et al., 2016). Hammar et al. (2016) warns that whilst the OWFs have potential for nature restoration, negative impacts associated with prospecting, installation and decommissioning should not be overlooked, and indeed be mitigated as well. Thus, nature-inclusivity in OWFs consists of both enhancement of positive ecological effects and simultaneously protecting from negative ecological impacts. Planning considerations, such as avoiding important recruitment habitats and by timing construction activities outside important breeding seasons, can reduce many potential negative impacts of OWFs on the marine ecosystem (Bergström et al., 2014). Mitigating negative impacts on seabirds as well as an established restriction on fishing are two other basic requirements for an OWF to function as a means of marine conservation (Hammar et al., 2016).

A central issue in marine conservation is scientific understanding the drivers of restoration success (Montero-Serra et al., 2018). It is therefore essential to monitor the distribution and population status of local marine life in OWFs and adjust its regulation and operations accordingly (WOZEP project team, 2016). The evidence base for ecological impacts of OWFs remains poor and urgently requires additional multi and interdisciplinary biodiversity-oriented research (Inger et al., 2009). What contributes to this knowledge scarcity are the excessive costs and logistical complexity of collecting field measurements in OWFs (WOZEP project team, 2016). Planning field work is highly weather dependent and should fit with scheduled vessel traffic of the OWF operator. Lack of funding for pilot studies is a constraint in progressing nature-inclusivity research in OWFs (Jansen et al., 2016).

2. Justification and research questions

With the invention of floating turbines and the increasing demand for renewable energy, it is abundantly clear that OWFs will continue to colonise ocean space globally, undoubtably colliding with the conflicting interests of other maritime sectors. There is wide agreement that OWFs have nature enhancing properties, due to the *reserve effect* and the *artificial reef effect*. These can be amplified by design options like optimised scour and cable protection. Hermans et al.'s (2020) catalogue of nature inclusive design solutions guides policy makers and developers in habitat creation for target species populations in OWFs. However, non-physical measures, such as planning around breeding and migration seasons, are also important for nature conservation. An inventory thereof is yet to be made. Without mitigation, the construction, operation, and decommissioning of OWFs indeed have destructive influences on the local marine life as well. Worryingly, there is limited scientific knowledge on the ecological risks of larger scale OWF deployment. Cumulative effects, biofouling invasions and the fate of novel artificial scour protection habitats upon the end-of-life point. These are amongst the unknowns within the realm of marine ecology in OWFs. Today this field of study, predominantly entailing novel pilot studies, is limited by the logistical complexity and steep costs of data collection. Consequently, it craves empirical validation in the form of efficient and scalable monitoring programmes with standardised methodologies.

To begin to address these knowledge gaps, the following questions were formulated, that this research project sets out to answer:

Q1. What solutions can be implemented in the design and planning of an offshore wind farm to mitigate its negative ecological impacts and enhances the positives?

> **Q1a.** Are these mitigation and nature enhancement solutions on market, in development or yet to be invented?
>
> **Q1b.** In light of large-scale expansion of OWFs and their long-term deployment in the marine space, what mitigation and nature enhancement solutions, take into account the incidental ecological risks and uncertainties of this trajectory?

Q1c. To what extent is nature inclusivity in OWFs adapted to trends in offshore renewable energy infrastructure, such as the rise of floating turbine technology, the growing competition over ocean space and the resulting need for co-locating varying maritime users?

Q2. How can marine life in OWFs be measured and quantified to best facilitate monitoring programmes thereof?

Q2a. How do species abundance and composition vary across scour, cable, sand and reef substrate in OWF Hollandse Kust Zuid?

3. Methodology

The methodology of this study (see figure 2) comprises both a qualitative literature review on the topic of nature inclusivity in OWFs as well as a quantitative evaluation of this topic in the form of a case study at OWF Hollandse Kust Zuid. The first part covers Q1a-c, by constructing a knowledge framework on nature inclusivity in OWFs. This commenced by gathering the existing scientific publications on the matter. These were summarised and thereafter expanded by including a broad range of critically evaluated open sources. This entailed grey literature, such as websites, social media announcements and publications by OWF developers, nature inclusive innovators and stakeholders alike. To produce a substantial body of new knowledge with the most up-to-date insights, a series of semi-structured interviews were conducted. All information was documented in the tabular overview and upon completion of interviews, summarised into a condensed framework summary. Q2, a case study, aimed to complement the framework, by demonstrating how the findings from Q1 merge into a field example. Outlined in the sections below, is an in-depth description of each of these methodologies.

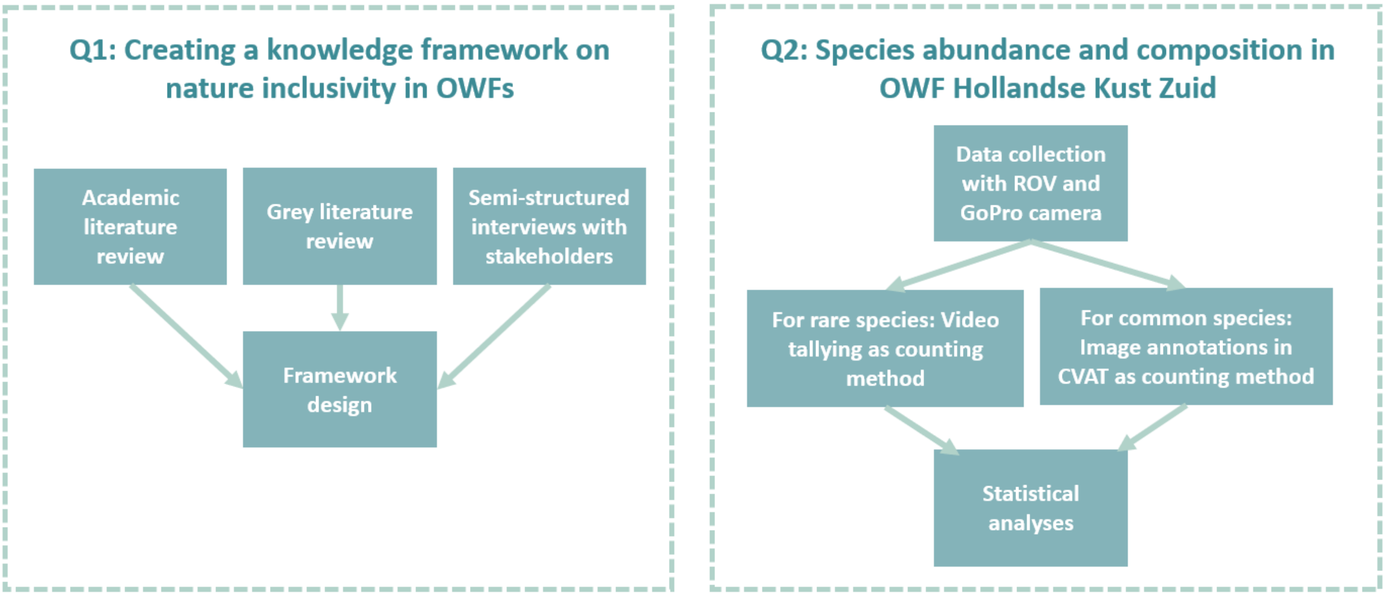


Figure 2. Flowchart visualising the methodology of this study in one glance. The chronology of data processing steps is grouped by research question.

3.1 Q1: Creating a knowledge framework on nature inclusivity in OWFs

3.1.1 Literature review

From July 2023 until December of 2024, an extensive search of academic libraries was carried out, including but not limited to the databases of WUR Library Search, UVA Library and Google Scholar, to collect suitable articles to include in the review. The search focussed on terms such as *offshore wind, OWF, wind energy, offshore renewables, nature inclusivity, nature inclusive, Nature Inclusive Design, NID, nature enhancement, nature restoration, environmental protection, nature conservation, marine conservation, marine ecology, marine biology, ecological impact, ecological benefits, ecological mitigation, environmental mitigation*. Papers including mention of the North Sea were selected by default, however those regarding other geographical areas were also taken into account when including one or more of the aforementioned search terms.

By focussing on publications touching on OWFs, the marine ecology therein, and nature restoration thereof, all information relating to Q1 was extracted and organised into a structured table. Peer-reviewed articles provide comprehensive and absolute information on studied topics. Given the innovative and market-driven nature of nature inclusivity in OWFs, it was decided that this study would be incomplete without analysing non-academic sources. These included materials published by OWF developers and manufacturers of nature inclusive solutions for OWFs directly. By including a wider breadth of information sources, this study goes beyond the realm of existing nature inclusive solutions and their measured ecological impact. It also paints a picture of nature inclusive solutions that are yet to be developed or do not yet exist, despite industry demand for them. Where the ecological impacts of non-existing nature inclusive solutions cannot be observed, let alone quantified, this study does include any details on expected or predicted outcomes of their placement. To standardise the grey literature review, websites were only included if accessible through the Google search engine, whereas news articles were only included if they were posted on LinkedIn. For both the websites and the news articles the same search terms were used as those mentioned above for academic literature. A second criterion for including sources in the grey literature review, was that they had to be either published by a stakeholder in one of the following profiles: offshore developer, nature inclusive solution manufacturer, consultancy, government or NGO.

3.1.2 Semi-structured interviews

Inspired by the data collection approach utilised by Hermans et al. (2020), it was decided to conduct a series of semi-structured interviews with stakeholders of nature inclusivity in OWFs (see appendix 1). A semi-structured interview consists of a predetermined list of open-ended questions to ask the interviewee. Yet it grants the interviewer to phrase and order the questions as deemed practical during the conversation (Young et al., 2018). This format enables subjects to provide information freely and expand into subtopics or narratives that the interviewer may not have considered. This was regarded as essential due to the exploratory nature of this study.

To encourage a diversity of perspectives to be voiced, a brief stakeholder analysis was conducted. This commenced with the identification of the types of people that influence or are influenced by nature inclusivity in OWFs. With every identity in this list, it was determined whether their perception of this topic is in favour, against or neutral. An estimation was made per stakeholder identity of the amount of power they assert over the outcomes of nature inclusivity in OWFs. With these parameters mapped, it became apparent what type of stakeholders had to be represented in the data collected from the interviews to assure multi-perspectivity therein. In finding voices willing to be interviewed, unfortunately regulatory bodies and policy makers were underrepresented in this research. This was due to a lack of response from individuals with this specific stakeholder profile. The interviewees represent a range of perspectives from across the OWF sector including OWF developers, contractor, grid operator, NGO, a research institute and startup. The table below summarises the stakeholder profiles of the interviewees:

Table 1. A list of the interviewees and a brief analysis of their respective stakeholder profiles.

	Date and location of interview	Stakeholder profile of employer	Function interviewee	Area of expertise interviewee	Contributions to nature inclusivity in OWFs	Expectations of nature inclusivity in OWFs	Power over nature inclusivity
1	12/11/2024, online	Offshore marine contractor	Specialist Coastal and marine ecosystems	Nature inclusive landscaping and species rehabilitation projects in OWFs	Constructs OWF and designs nature inclusive solutions in OWFs	Supporter	Significant
2	14/11/2024, online	OWF operator	Offshore wind energy consultant	Environmental permits for OWFs and impact assessments and monitoring requirements for OWFs	Manage and monitor nature inclusivity efforts in OWFs	Supporter and critic	Considerable
3	18/11/2024, online	Energy company (OWF developer and operator)	Marine ecology specialist	Ecological tender criteria and biodiversity strategy for renewable energy sector to make a net positive contribution to nature	Design, procure, implement, manage nature inclusivity efforts in OWFs	Supporter	Significant
4	20/11/2024, online	NGO	Project lead nature-friendly offshore wind	Ecological risks and opportunities of OWFs and policy requirements for nature-friendly OWFs	Advocates for nature protection in the marine environment	Supporter and critic	Limited
5	20/11/2024, online	Energy company (OWF developer and operator)	Marine ecologist	Ecological permit requirements for new OWF tenders and ecological monitoring requirements for operational OWFs	Plan, deisgn, procure, implement, manage nature inclusivity efforts in OWFs	Supporter	Significant
6	22/11/2024, online	Grid operator	Marine ecologist	Nature inclusive cable design and the influence of electromagnetic fields on marine species	Plan, design, procure, implement, manage nature inclusivity efforts in OWFs	Supporter and critic	Considerable
7	26/11/2024, online	Research institute	Marine biology researcher	Net positive approaches and design for coastal hard works and functional analysis of benthic communities	Researches and monitors nature in OWFs	Critic	Considerable

All interviews were carried out over video call, to minimise travel time. Each interview lasted up to one hour. Notes were taken to capture the answers of the interviewee in a concise format, avoiding the need to transcribe conversation. Interviews were deliberately not recorded to put less pressure on interviewees in formulating themselves perfectly. All interview summaries can be found in appendix 1.

3.1.3 Framework design

Considerable thought went into designing a framework to maximise relevant knowledge on the topic of nature inclusivity in OWFs. A key outcome of this study is to organise a large amount of information on a broad topic from a wide range of sources. Therefore, it was important to establish an overarching categorisation within this knowledge framework first. To best summarise outcomes in a logical and orderly visualisation, it was decided that spatial components of an OWF form the overarching categorisation (see figure 3). In this framework spatial components of an OWF include:

1) **Layout and location**: This category contains ecological impacts and solutions relating to the biogeographical site and situation of an OWF. As well as to those aspects of OWF design and planning that are not specific to one part of its build, but rather relate to multiple or all infrastructural components.
2) **Tower and blades**: This category contains all ecological impacts and solutions that are centred around the components of wind turbines above water. Including their tower, blades, nacelle and rotor.

3) **Foundation**: The foundation is the below water component of the turbine. Three types of foundations are fixed to the bottom. Therefore they must contain scour protection, which is rock material to withstand seabed erosion. These fixed-bottom foundations include monopiles and jackets. With floating foundations, the turbine is constructed on a buoy attached with anchor lines. Some ecological impacts and solutions will only refer to one foundation type. Foundations not only exist for turbines, but also for substations, hydrogen turbines and energy islands.
4) **Scour and cable protection**: Scour protection is required to prevent seabed erosion around OWF infrastructure, such as turbines, array and export cables, and cable crossings.
5) **Complementary infrastructure**: Anything that is not part of its base case design of an OWF but rather serves dual-use (such as aquaculture and nature protection) or co-location purposes (such as offshore hydrogen and floating solar power).
6) **Outside of OWF**: Not under the direct mandate of OWF developers, or in the direct vicinity of an OWF.

Within these six categories, a sub order was created based on lifecycle occurrence. The lifecycle categories were adjusted from DHI (2021), and chronologically include: *Site selection*, *Development*, *Construction*, *Operations*, *Decommissioning*, and lastly the category *All stages*, referring to a nonspecific time period.

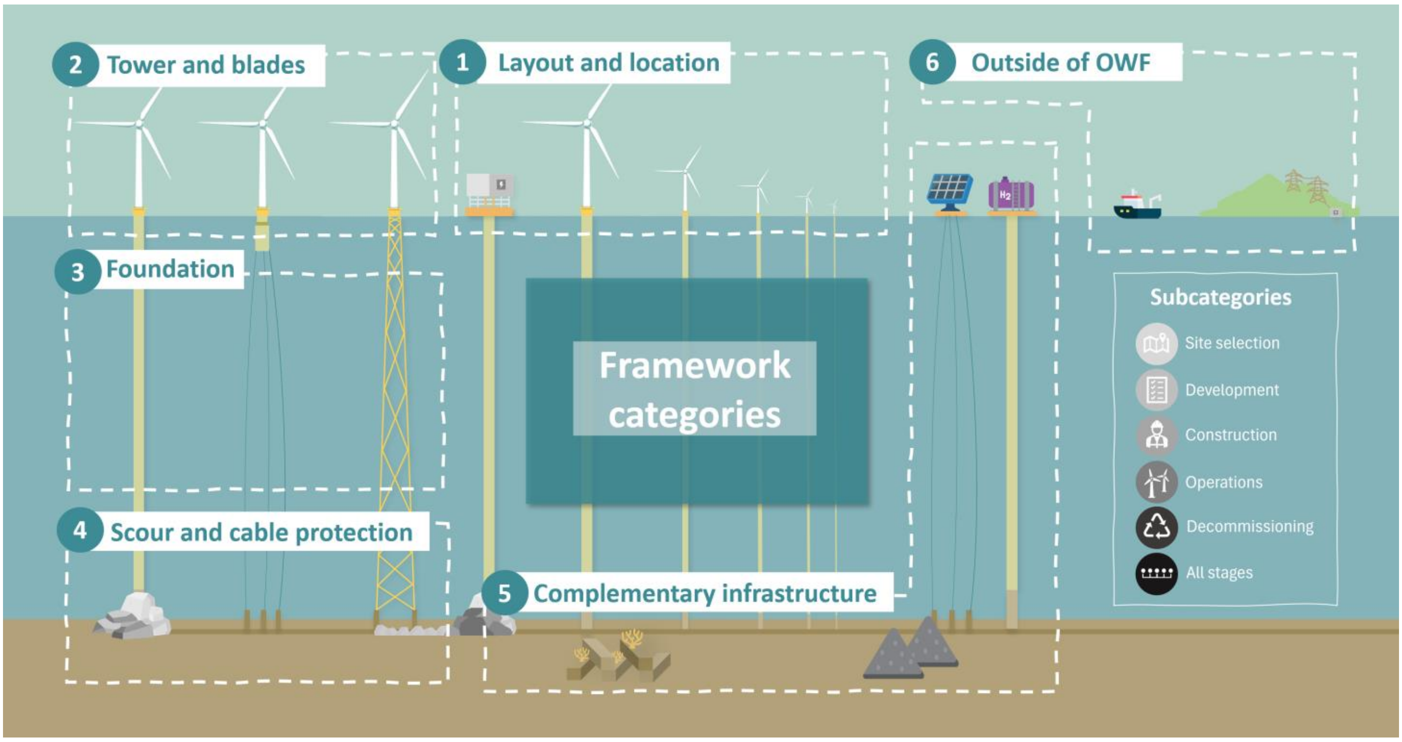


Figure 3. A visual aid to demonstrate the spatial categories and temporal subcategories of the framework design.

All findings on nature inclusivity in OWFs were packaged into pairs of ecological impacts and their respective solutions. Ecological impacts were described and marked with associated receptor species groups as defined in Vrooman et al. (2019): Marine mammals, birds, bats, fish and benthic species. Furthermore, the ecological impacts of OWFs where color coded in the framework in accordance with their classification within the Mitigation Hierarchy (Bennun et al., 2021; Leander Vølstad et al., 2022; Xodus Group & The Rich North Sea, 2024):

- **Avoidance**: The most important category for mitigating ecological impacts, which includes actions taken to prevent the impact in the first place.
- **Minimisation**: Applies to unavoidable ecological impacts and contains measures taken to reduce the severity thereof.
- **Restoration**: The reversing of damage to the ecosystem, which can also include repairing ecological degradation from previous industrial activities, such as overfishing.

- **Offsets**: Compensation for ecological impacts that cannot be handled by any of the above measures and can instead be concentrated in a geographically different region.

The solutions paired to ecological impacts of OWFs were labelled to distinguish between their maturity using a simplified version of the Technological Readiness Level (TRL) categories defined by RVO (Rijksdienst voor Ondernemend Nederland, 2022), which include:

- **Discovery phase**: The fundamental concepts and applications of an innovation (i.e. nature inclusivity solution) are being researched and better understood.
- **Development phase**: Proof-of-concepts of the innovation are in development and prototypes tested in pilot environments.
- **Demonstration phase**: Prototypes of the innovation are demonstrated in operational environments for practical insights and practice its market compatibility.
- **Deployment phase**: The innovation is on-market and fully operational.

Furthermore, solutions were labelled with the stakeholders that have influence over their execution. The stakeholder profiles were taken from GROW (2024) and include: Regulatory bodies, NGOs, Research & consultancy, Installation contractors, Offshore wind developers, Multi-user innovators and startups.

It was decided to produce an elaborate framework in table format using Microsoft Excel and to design a concise summary infographic in Microsoft PowerPoint.

3.2 Q2: Species abundance and composition in OWF Hollandse Kust Zuid

This case study was undertaken in a supporting capacity to the Costs and Biodiversity of Nature-Inclusive Energy (KOBINE) project, led by Oscar Bos from Wageningen Marine Research. Commissioned by the Dutch Ministry of Agriculture, Nature and Food Quality (Ministerie van Landbouw, Natuur en Voedselkwaliteit), the KOBINE project sets out to quantify the nature gain (biodiversity) of various nature-inclusive designs in nature restoration projects in offshore wind farms (or test areas outside), in relation to their construction and maintenance costs (Wageningen University and Research, 2024). As part of the KOBINE project, Bos took video transects of marine life in OWF Hollandse Kust Zuid. The processing and analysis of this data was incorporated into this Msc research project to complement the framework, with an applied perspective. This case study is a pilot study. Its data collection, analysis and interpretation must be understood as a proof-of-principle study. It aims to support future monitoring programmes in identifying difficulties that occur in surveying in the OWF marine environment. In this environment, some variables are impossible to control and thus measurements difficult to standardise and replicas expensive to collect. Hence this case study sets out to explore the best research practices under these considerable constraints.

3.2.1 Field data collection

Data collection took place on the 26th and 27th of September 2023 in Kavel I of OWF Hollandse Kust Zuid (HKZ). This OWF is operated by Vattenfall and located 18 - 36km from the coast of the Netherlands (see inset map in figure 4). A Remotely Operated Vehicle (ROV) was operated by BeeX (www.beex.sg) (BeeX, 2024) to collect video footage at the foundation of four bottom-fixed turbines, two of which contain a nature inclusive reef patch. Turbines D1 and D2 (see figure 4) are the two turbines fully surrounded by ordinary scour protection, with a grain size of about 10x10cm per boulder. Turbines A3 and B2 (see figure 4) both contain an artificially constructed reef path to one side of their foundation. These rock reefs consist of boulders with sizes varying between 50x50 and 120x120cm and each have a total surface area of approximately 200m^2. HKZ has a total of nine such artificial rock reefs within its park boundaries.

Built into the BeeX ROV is a positioning system to track its flight path spatially (see figure 4). This allowed for the calculation of m^2 captured in the video footage and thereby estimate species abundance per unit area. A GoPro camera was attached to the BeeX ROV separately to guarantee HD and 4k image quality. Swimming at a set distance of 1 m

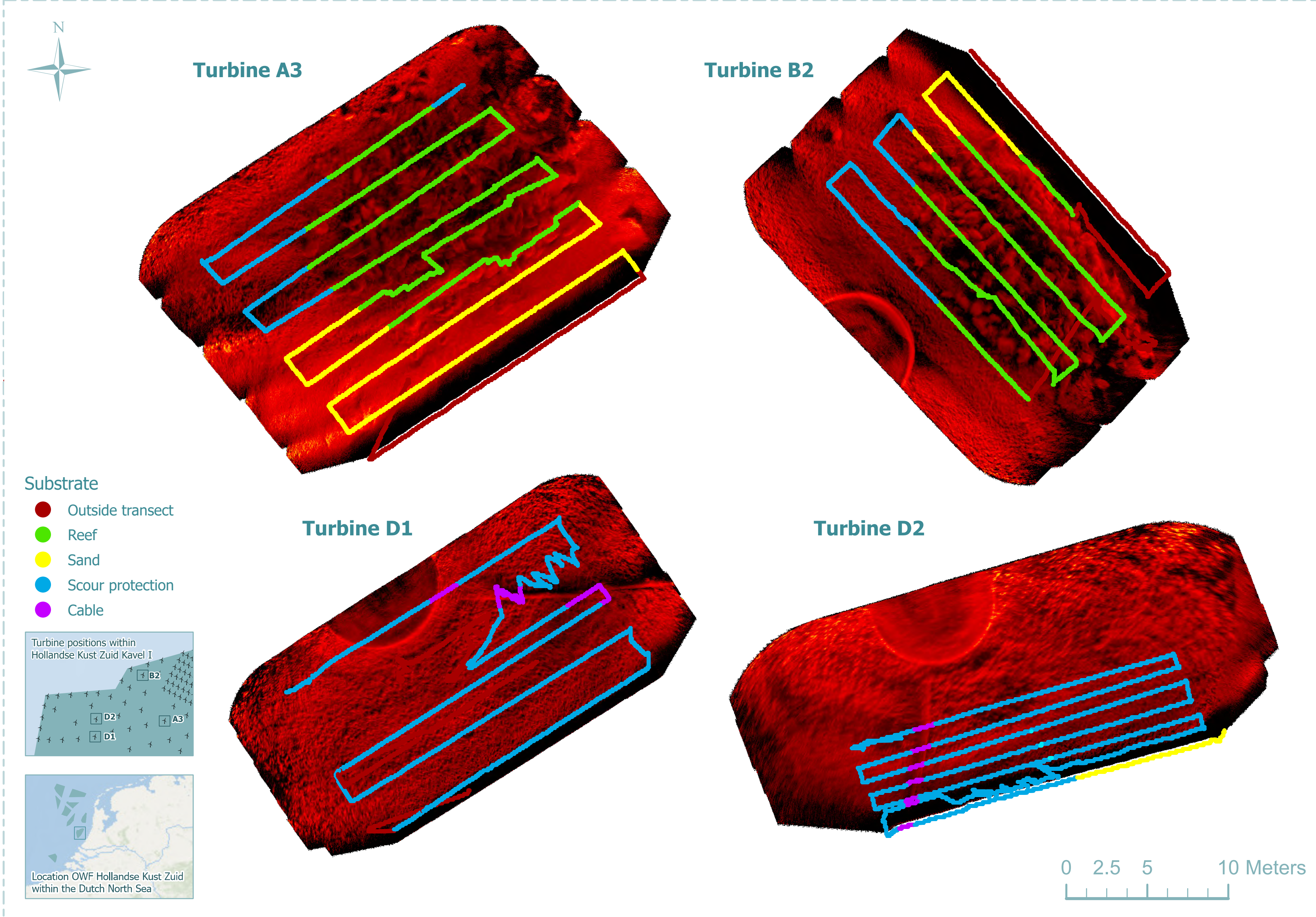


Figure 4. A spatial overview of the four turbine locations within Dutch OWF Hollandse Kust Zuid, where the video footage for this study was collected. Here the flightpaths at each site are color coded by substrate (reef, sand, scour protection or cable) and the coordinates of their trajectory are overlayed with a depth sonar mosaic both of which were recorded by BeeX. Data used in inset maps is sourced from Esri Nederland.

above the sea floor, makes the width of the transect belt approximately 1 m, as tested with the angle of the camera. The length of the transect belts at each site could thus be used as the area covered in m^2. To avoid overlap, the small sections of the flight path where the ROV changes lanes, are left out of this area calculation.

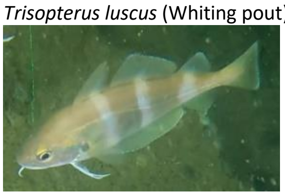
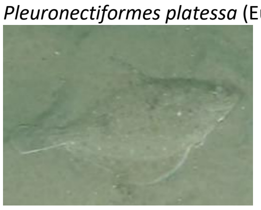
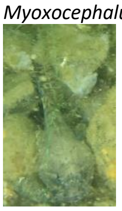
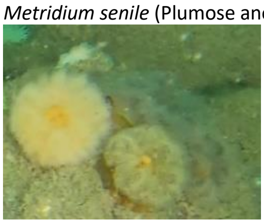
The ROV was preconfigured to swim a standard pattern at every turbine location. However its movement was influenced by surge and currents once submerged. The direction of its flightpath also altered slightly when bumping into bottom features, such as the reef or cable substrates. Hence the m^2 surveyed is not uniform across locations nor across substrate types (see table 2). The cumulative area surveyed of all four locations is 509.46 m^2, of which 151.98 m^2 is reef, 268.6 m^2 is scour protection, 15.17 m^2 cable and 73.71 m^2 sand substrate.

The ROV, weighing approximately 70kg, was let in the water when current speeds where smaller than approximately 1 knot. Nevertheless, the swimming speeds still varied considerably per turbine location, with strong surge and current in the afternoon thus impacting mostly B2. These parameters are impossible to control because site visits to OWFs are expensive and planned well in advance and despite the weather forecast. Hence the duration (in minutes) of the videos transects captured at the four different locations is also not completely similar (see table 2). Video transects consist of several .mp4 files due to the auto-recording loop configurations that the GoPro was set to. This meant that once the ROV entered the water, it continued to recorded even after its limit of 8 minutes and 52 seconds was reached.

Table 2. Overview of video footage timings and whether conditions encountered at each turbine location surveyed with the ROV during the field work in OWF Hollandse Kust Zuid.

Location	**Turbine A3**	**Turbine B2**	**Turbine D1**	**Turbine D2**
Date	25-09-2023	25-09-2023	26-09-2023	26-09-2023
Water entry time	10:09	16:00	11:55	13:00
Water exit time	10:37	16:22	12:30	13:27
Total area surveyed (in m^2)	159.77	104.05	99.1	146.54
Reef area surveyed (in m^2)	80.56	71.42	0	0
Scour protection area surveyed (in m^2)	27.03	20.76	91.77	129.04
Sand area surveyed (in m^2)	52.18	11.87	0	9.66
Cable area surveyed (in m^2)	0	0	7.33	7.84
Visibility (as derived from field observations made by boat crew)	Medium	Poor	Good	Good
Surge and current (as derived from field observations made by boat crew)	Medium	Strong	Weak	Weak
Camera	GoPro Hero 11	GoPro Hero 11	GoPro Hero 11	GoPro Hero 11
Duration of transect (excluding swimming time for water entry/exit)	24 minutes and 10 seconds	25 minutes and 28 seconds	25 minutes and 22 seconds	25 minutes and 31 seconds
Video file names (.mp4 format)	GX030094 (transect starts at 00:56); GX040094; GX050094 (transect ends at 07:22)	GX040096 (transect starts at 06:51); GX050096; GX060096; GX070096 (transect ends at 05:43)	GX020099 (transect starts at 06:20); GX030099; GX040099; GX050099 (transect ends at 05:06)	GX020100 (transect starts at 05:05); GX030100; GX040100; GX050100 (transect ends at 03:00)
Number of frames analysed per file	30; 33; 28	7; 33; 33; 22	9; 33; 33; 19	14; 33; 33; 11
Total number of frames analysed	91	95	94	91

Table 3. Species list of the *Decapoda*, *Echinoderms*, *Mullusca*, *Pisces* and *Anthozoa* that were counted in this research project, either through the CVAT annotation counting method, the video tallying counting method or both.

Decapoda		
Cancer pagurus (Brown crab)  CVAT annotation counting method	*Necora puber* (Velvet swimming crab)  CVAT annotation counting method	*Pagurus bernhardus* (Hermit crab) Not spotted CVAT annotation counting method
Echinodermata		
Asterias rubens (Common starfish)  CVAT annotation counting method	*Ophiotrix fragilis* (Common brittle star) Not spotted CVAT annotation counting method	*Ophiura ophiura* (Serpent star)_  CVAT annotation counting method
Mollusca		
Mytilus edulis (Blue mussel)  CVAT annotation counting method	*Crepidula fornicata* (Common Atlantic slippersnail)  CVAT annotation counting method	
Pisces		
Callionymus lyra (Common dragonet)  Both the CVAT annotation counting method and the video tallying counting	*Trisopterus luscus* (Whiting pout)  CVAT annotation counting method	*Mullus surmuletus* (Striped red mullet)  Both the CVAT annotation counting method and the video tallying counting
Pholis gunnellus (Rock gunnel)  Both the CVAT annotation counting method and the video tallying counting	*Gadus morhua* (Atlantic cod)  Both the CVAT annotation counting method and the video tallying counting	*Pleuronectiformes platessa* (European plaice)  video tallying counting method
Parablennius gattorugine (Tompot blenny)  video tallying counting method	*Trisopterus minutus* (Poor cod)  video tallying counting method	*Myoxocephalus scorpius* (Shorthorn sculpin)  video tallying counting method
Anthozoa		
Cylista troglodytes (Mud sagartia)  CVAT annotation counting method	*Metridium senile* (Plumose anemone)  CVAT annotation counting method	*Actinothoe sphyrodeta* (Sandalled anemone)  CVAT annotation counting method

3.2.2 Pre processing

Two counting methods were used to record species abundance accurately yet efficiently at the four turbine locations. For the species that were rare - less than a dozen sightings per transect - , the full video footage was viewed. Upon sighting, an individual was first identified, where possible to species level, otherwise family. Then tallied, and thereafter verified by a fish or benthos specialist within Wageningen Marine Research. Table 3 contains an overview of the species included in this video tallying counting method. It also depicts the species counted through the CVAT annotation method which is described next.

Many species were abundantly present, and their quantities could not be counted fully over the length of the 24 to 25 minute video transects, given the time constraints of this projects. Therefore, it was decided to annotate still frames of half of the transect length and multiply these counts by two. This provides an estimation of the species abundance per m2 of the associated substrate and turbine location. An appropriate still frame interval was calculated. The length of every .mp4 video was 8 minutes and 52 seconds, which equates to 532 seconds. In every second the GoPro video quality enables users to extract 24 distinct still frames (i.e. photos), meaning that every .mp4 file consisted of 532 x 24 = 12768 frames.

The average swimming speed of the ROV enabled it to swim into a completely new view extent in 8 seconds: A benthic organism or other object coming into view, would be passed and out of view 8 seconds later. This means that if every unique view on the transect was to be analysed, a frame interval of 24 x 8 = 192 could have been retained to annotate the fully coverage of the transects. However, an annotation interval of 2 x 192 = 384 was kept instead, which in total meant approximately 33 still frames annotated per video file. And per transect, a total of 91 to 95 still frames were annotated.

3.2.3 Image annotations in CVAT

For every video transect 91 to 95 still images were annotated in a web-based application named Computer Vision Annotation Tool (CVAT, 2024). This is an image and video annotation tool used for labelling data for computer vision algorithms. All video files were neatly categorised in CVAT's cloud storage space (see figure 5a), from where they could be opened in the CVAT annotation interface (see figure 5b). Here bounding boxes were drawn around every visible marine organism, taking care to neatly place them on the boundary between object and backdrop. Organisms were labelled to species level, where distinguishable to such, otherwise family level.

Annotations were exported from CVAT into .xlsx format to summarise species counts in Microsoft Excel (v16.0) and adjust total counts by the relative m^2 surveyed of their respective substrate and turbine location. As these cumulative numbers were found to be very small, it was decided to multiply them by 100 and represent species abundance per 100 m^2 instead. The R library *ggplot* was utilised to plot the species abundances per 100m2 across substrates in both counting methods, to enable the analysis of statistically insignificant trends with the appropriate caution.

A csv file was exported to conduct statistical tests in RStudio (version 4.4.1). Species abundances per 100 m^2 per substrate category were found to be not normally distributed. Thus, the nonparametric Kruskal-Wallis test was performed to find statistically significant differences in the abundance of each species, per substrate in both counting methods. This was followed by a pairwise comparisons, conducted by Dunn's Test of Multiple Comparisons with a Bonferroni correction. Dunn's Test was chosen as the comparison between substrate groups, instead of comparisons to a control group.

Refer to appendix 2 for the raw data of both counting methods and appendix 3 for the R script of figures and statistics.

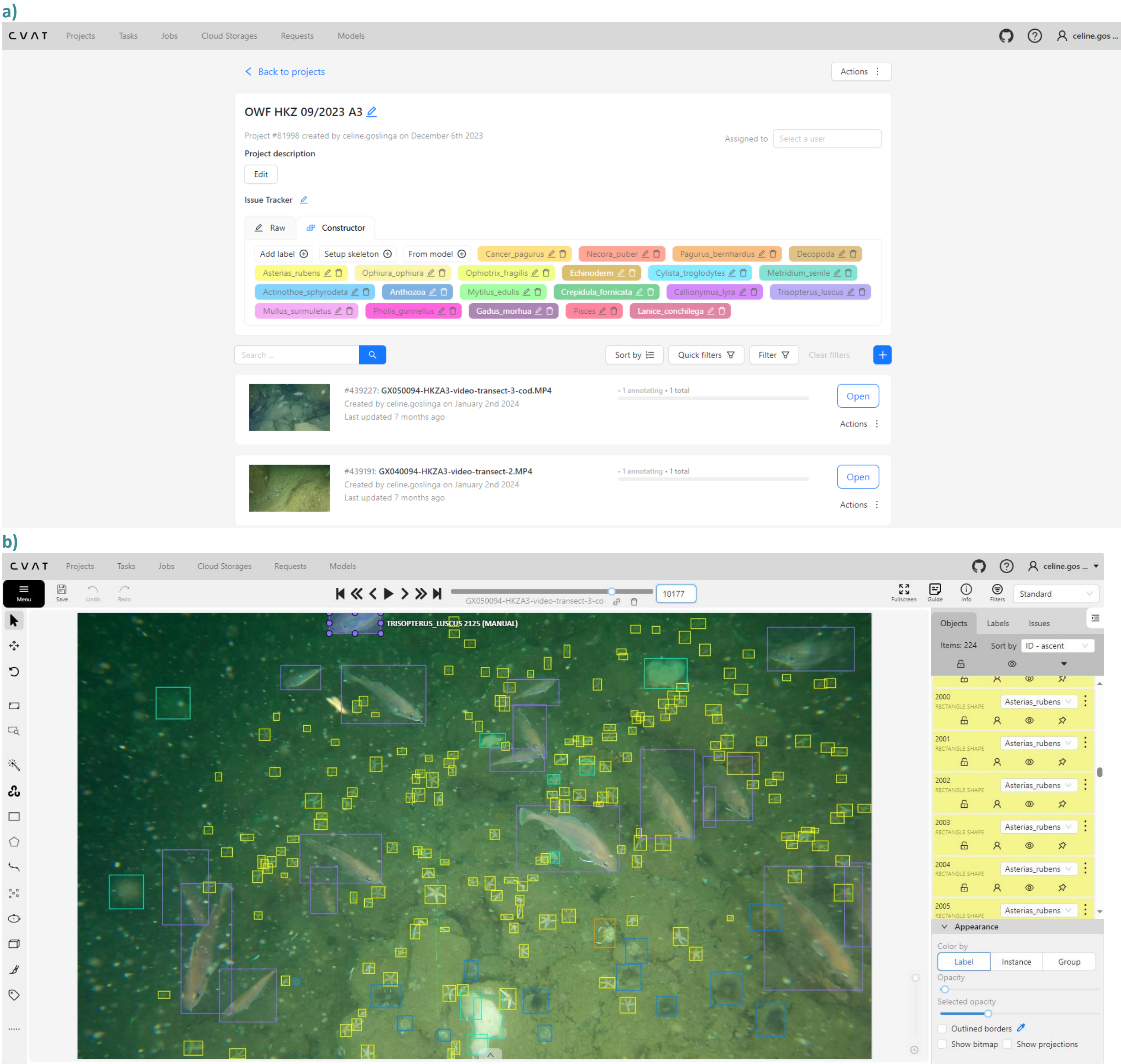


Figure 5 a) CVAT landing page, organises imagery into *projects*, *tasks* and *jobs*, with a set of annotation labels. **b)** The annotation interface has labelling tools on the left side, annotations on the right and enables navigation through the still frames of a video by scrolling through the top bar.

4. Results

4.1 Q1: A knowledge framework on nature inclusivity in OWFs

Table 4 represents the main result of this study, a framework of mitigation and nature enhancement solutions to implement in OWF design and planning to conserve marine ecosystems. Table 4 is the comprehensive version of all attained and processed knowledge on nature inclusivity in OWFs. The infographic (figure 6) complements table 4, by acting as a visual aid. It includes all ecological impacts and respective solutions as the framework in table 4, using the same numbering, though in shortened descriptions. To further classify nature inclusivity in OWFs in terms of its implementation availability, table 5 summarises table 4. Again, using the same numbers and shortened descriptions as initiated in the summary infographic (figure 6), table 5 orders and groups the ecological impacts of the main framework (table 4) according to their mitigation status and TRL. This tabular summary helps distinguishing which solutions exist on the market; are upcoming and in development; or still non-existent and missing, in the sense of leaving ecological impacts of OWFs unaddressed. The section below first chronologically summarises what can be found in the framework (table 4). Then, analysing the summary table (table 5) and summary infographic (figure 6), a description is provided of the existing, upcoming and missing solutions to ecological impacts, according to the framework proposed by this study.

4.1.1. Layout and location

Firstly, the section *Layout and location*, contains ecological impacts and solutions relating to the biogeographical site and situation of an OWF. When a government authority selects OWF sites to allocate to a development tender, there are myriad mitigation solutions to minimise and even avoid negative impacts entirely within the site selection phrase of the OWF lifecycle. Nature inclusivity in OWFs begins with starts with site allocation decisions that policy makers are faced with: Wherever installations should be located, determines whether OWFs should be designed to either minimise negative environmental impacts or indeed facilitate ecosystem restoration (Inger et al., 2009). Biotope influence site suitability of OWFs (DNV and NIVA, 2023), ideally ecologically valuable areas and important recruitment habitats are avoided entirely (Bergström et al., 2014). However, OWFs can be powerful means of conservation, when located in favor of marine connectivity or in areas of importance for ecological functions such as reproduction (Hammar et al., 2016).

This section also contains those aspects of OWF design and planning that are not specific to one part of its build. Rather solutions relating to multiple infrastructural components or overarch the layout of the park entirely. For instance, ecological degradation occurs from the sediment dispersal, fuel pollution and other vessel-associated waste injected into these sites (Bennun et al., 2021). At microscopic scale, phyto- and zooplankton are adversely affected during construction works. The wave effect, the shading effect and oxygen depletion lead to a 60% reduction in zooplanktonic biomass and a fluctuation in primary production of 10% (Wang et al., 2024). The wave effect refers to alternations in water quality and hydrodynamics that are caused by presence of OWF's monopile in the water column. Reduced wind speeds in the wake of the wind turbine, for example, affects turbulence, wave energy, current conditions and vertical movement of water masses which can alter water stratification (Leander Vølstad et al., 2022). At ocean-basin scale, further changes to hydrographical conditions caused by OWFs are very small, and would only be for importance in narrow water passages (Hammar et al., 2010). The shading effect refers to the local blocking of the sun by the monopile and spinning blades, which change water temperature and thereby the distribution of suspended particles and nutrients (Wang et al., 2024).

4.1.2. Tower and blades

OWFs can obstruct movement between breeding colonies and disrupt migration routes (Vrooman et al., 2019). Such barrier and displacement effects are posed on not only on birds, but also marine mammals, turtles and fish (Bennun et al., 2021). Marine mammals, such as porpoises, are thought to avoid OWFs because of their acoustic disturbance and electromagnetic fields, more on which later. The second section of the framework elaborates further on disruptions of OWFs to avian species, and possible means of preventing this. *Tower and blades* contain all ecological impacts and solutions that are centred around the components of wind turbines above water, including their tower, blades, nacelle and rotor. Above water, it is mostly the serious injury or death caused by collision with the spinning turbine blades in the turbine rotor swept zone, that poses a major threat to both migrating and sea-foraging birds (Hammar et al., 2016). In avoiding crashing into turbine blades, the migration routes of birds are altered above the surface. Design solutions include visual cues and maintenance of the minimum turbine air gap (SSE Renewables, 2021), whilst an operational example is the curtailing of turbines when key species, like the sea eagle, are within collision range (Bennun et al., 2021).

Table 4. Nature inclusivity in offshore wind farms: A framework of mitigation solutions to implement in Offshore Wind Farm (OWF) design and planning to conserve marine ecosystems.

This framework organises pairs of mitigation solutions and ecological impacts as they exist within OWFs. Some solutions relate to multiple ecological impacts, and some impacts can be solved through a number of solutions. The framework should be read from left to right with the fifth (colourful) column indicating which solutions relate to which ecological impacts and how. Furthermore, to best organise all mitigation solutions that can be implemented in OWFs to conserve marine ecosystems, it was decided to first group solutions and impacts by location and then by lifecycle occurrence. However, it must be noted that some solutions and ecological impacts do not strictly fall into one or another spatial or temporal category. Ordering all information on this topic into the respective where and when of their being, was reasoned to help convey this complex and multifaceted topic into a structured and digestible manner to readers, but simultaneously found to oversimplify the matter and thus should only be taken as general help to ease interpretation of the intertwined reality of nature inclusive solutions in OWFs.

Where	When	Solution	Ecological impact
What geographic or materialistic component of an OWF, is most relevant to the solution. Categories invented in this paper.	At what point in the life cycle of an OWF, is a solution most relevant to implement. Categories adjusted from DHI (2021): Site selection Development Construction Operations Decommissioning All stages	These three columns characterise mitigation solutions, through description, and by identifying the two other traits of the solution. Firstly, Technological Readiness Level (TRL) innovation maturity categories defined by the RVO (Rijksdienst voor Ondernemend Nederland, 2022): **Discovery phase:** The fundamental concepts and applications of an innovation (i.e. nature inclusivity solution) are being researched and better understood. **Development phase:** Proof-of-concepts of the innovation are in development and prototypes tested in pilot environments. **Demonstration phase:** Prototypes of the innovation are demonstrated in operational environments for practical insights and practice its market compatibility. **Deployment phase:** The innovation is on-market and fully operational. Secondly, solutions are marked with the stakeholder profile of those parties that can be understood to have a load-bearing responsibility over their execution. Using stakeholder profiles as defined by GROW (2024): Regulatory bodies; Research & consultancy; Offshore wind developers; NGOs; Installation contractors; Multi-use innovators & startups	These three columns characterise ecological impacts of OWFs, through description, and by identifying the two other traits. Firstly the type of mitigation of a given solution to this impact. These mitigation types are classified by the Mitigation Hierarchy (Bennun et al., 2021; Leander Vølstad et al., 2022; Xodus Group & The Rich North Sea, 2024): **Avoidance**: The most important category for mitigating ecological impacts, which includes actions taken to prevent the impact in the first place. **Minimisation**: Applies to unavoidable ecological impacts and contains measures taken to reduce the severity thereof. **Restoration**: The reversing of damage to the ecosystem, which can also include repairing ecological degradation from previous industrial activities, such as overfishing. **Offsets**: Compensation for ecological impacts that cannot be handled by any of the above measures and can instead be concentrated in a geographically different region. Secondly, ecological impacts of OWFS are marked with associated receptor species groups. Categories adjusted from Vrooman et al. (2019): Marine mammals; Fish; Multiple trophic guilds; Birds; Benthic species; Unclear; Bats

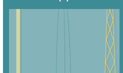
1. Layout and location: This category contains ecological impacts and solutions relating to the biogeographical site and situation of an OWF as well as to those aspects of OWF design and planning that are not specific to one part of its build, but rather relate to multiple infrastructural components or the park as a whole.

When within OWF life cycle to best implement solution	*Stakeholders responsible for solution*	*TRL of solution*	*Solution description*	*Type of mitigation of solution to impact*	*Ecological impact description*	*Receptor of ecological impact*
Site selection	Regulatory bodies	In development	**Solution 1.1:** Through international collaboration on marine spatial planning, policy makers can group nature conservation efforts across OWF development areas, instead of approve fragmented small OWF specific projects across an ocean or sea basin. By area wide planning instead of park planning, marine restoration efforts, such as oyster reintroduction, will be more effective (Interview #1, 2024).	>>> Restores >>>	**Ecological impact 1.1:** OWFs can be powerful means of conservation, when located in favor of marine connectivity or in areas of importance for ecological functions such as reproduction (Hammar et al., 2016).	Multiple trophic guilds
	Research & consultancy	In deployment	See --> **Solution 6.9** (further research into marine ecosystems and OWFs) and **Solution 6.10** (further research into enabling monitoring technologies).	>>> Unknown >>>	**Ecological impact 1.2:** Unknown cumulative hydrodynamic influences of offshore wind farms. The projected large scale presence of wind turbines at sea will cause changes in stratification and mixing of the water column thereby affecting temperature, available light, nutrients and primary productivity and possibly higher trophic guilds in response (Interviewee #1, 2024).	Multiple trophic guilds, Unclear
	Regulatory bodies	In deployment	Solution 1.2: Use non-price criteria in the tender of an offshore wind lot to reward projects built with low biodiversity impact and located on degraded or non-pristine maritime areas (DNV and NIVA, 2023) and encourage developers to design based on what restoration task is required in a specific area (Interviewee #3, 2024), for instance further away from shipping routes, an emphasis on maintaining silence is effective.	>>> Avoids >>>	**Ecological impact 1.3:** Avoid and minimise destruction of biodiversity already present in the selected location of an OWF (Bureau Waardenburg, 2020). Biodiversity already present van be understood as ecologically valuable habitat, which includes Marine Protected Areas (MPAs), Important Marine Mammal Areas (IMMAs), Key Biodiversity Areas (KBAs), Ecologically or Biologically Sensitive Areas (EBSAs), Particularly Sensitive Sea Areas (PSSA); Areas supporting threatened ecosystems or species, such as offshore foraging areas, breeding grounds; Areas along migratory corridors that support high concentrations of birds, marine mammals and fish; Important nesting, roosting, foraging and overwintering areas for birds and bats in coastal areas where the offshore wind farm cable makes landfall; Areas that concentrate species' movements, such as sandbanks, coastal wetlands and marshes and coastal areas of high relief such as ridges and cliffs (Bennun et al., 2021).	Multiple trophic guilds
		In deployment	**Solution 1.3:** Designate OWF development lots outside of ecologically valuable areas entirely. According to Inger et al. (2009), policy makers decided wherever OWF installations should be located, determine whether an OWFs can be designed to either minimise negative environmental impacts or indeed facilitate ecosystem restoration (Inger et al., 2009).	>>> Avoids >>>		
Development	Offshore wind developers	In deployment	**Solution 1.4:** Within the micrositing process of designing of the OWF layout, avoid designating any infrastructure (turbines, cables or other) around ecologically valuable habitat, at risk species' habitat and important recruitment habitats (DNV and NIVA, 2023; Bergström et al., 2014).	>>> Avoids >>>		
	Offshore wind developers, Installation contractors	In demonstration	**Solution 1.5:** Adjust the scheduling of the construction and disassembly to take place outside of sensitive periods such as migration season and spawning, nursing and breeding periods (Bennun et al., 2021).	>>> Avoids >>>		
		In deployment	See --> **Solution 3.9** (Use Acoustic Deterrent Devices).	>>> Minimises >>>	**Ecological impact 1.4:** When Unexploded Ordnances (UXOs) are located in the OWF location and require detonation to commence in construction of the OWF, the noise unleased in this process impacts marine mammals and fauna (Xodus Group & The Rich North Sea, 2024).	Marine mammals, Fish
	Offshore wind developers	In development	**Solution 1.6:** When there is a clear migration or movement direction (for instance between roosting and feeding areas), a flight corridor can be incorporated into the turbine layout (Bennun et al., 2021). Considerations in the turbine arrangement can help reduce barriers to bird movement thereby decreasing risk of collision. Such flight corridors can be realised by aligning widely-spaced turbine clusters that run parallel to, rather than across, the predominant flight direction (Bennun et al., 2021).	>>> Minimises >>>	See -> **Ecological impact 2.3** (Reduced survival rates of avian species due to collision).	Birds, Bats
	Regulatory bodies	In development	**Solution 1.7:** Within the Environmental Impact Assessments of OWF tender proposals, allow for developers to include the positive ecological impacts they will factor into their plans, which can relate to one or many parts and locations within the OWF design (DNV and NIVA, 2023).	>>> Restores >>>	See --> all ecological impacts with a restoration mitigation solution.	Multiple trophic guilds
		In development	**Solution 1.8:** Increase funding and financial resources available to invest in nature inclusivity in OWFs (DNV and NIVA, 2023). For instance, subsidise additional heterogeneous rock layer on the scour protection or research into quiet installation technologies.	>>> Restores >>>		
Construction	Installation contractors	In deployment	**Solution 1.9:** To minimise sediment suspension, construction zones are to be allocated to the minimum areas necessary to complete the installations of OWF infrastructure, and contractors should not deviate outside these zones (Defingou et al., 2019).	>>> Minimises >>>	**Ecological impact 1.5:** During construction works, the total area of benthic habitat destruction varies depending on the type of foundation being installed, but regardless of the extent, always some amount of ecological degradation occurs from the sediment dispersal and associated turbidity, which block sunlight penetrating through the water column.	
All stages	Multi-use innovators & startups	In development	**Solution 1.10:** Stimulate and develop low- and net-zero-carbon marine biofuels to help decarbonize maritime transport and allow for vessel waste to biodegrade with limited harm to the environment (Ovrum, 2023).	>>> Avoids >>>	**Ecological impact 1.6:** Particularly during construction works but also later on, throughout operational maintenance and disassembly of OWFs, boat traffic pollutes the marine ecosystem from fuel and other vessel-associated waste injected into these sites. Increased boat traffic can be anticipated from the development of offshore energy islands, hydrogen fuel stations and co-location with other maritime sectors.	Multiple trophic guilds
	Offshore wind developers, Installation contractors	In deployment	**Solution 1.11:** Minimising vessel movement and instigating vessel speed limits throughout all phases of OWFs lifecycle (Defingou et al., 2019).	>>> Minimises >>>		
	NGOs, Research & consultancy	In deployment	**Solution 1.12:** Enforce marine research monitoring programmes within and across OWFs; Encourage collaborations between OWF developers, NGOs and academic institutions; Praise knowledge and data sharing across stakeholders; Stimulate publications of scientific findings to the public domain to progress collective knowledge on the ecological impacts, positive and negative, of OWFs (DNV and NIVA, 2023).	>>> Minimises >>>	See --> all ecological impacts with a restoration mitigation solution.	
	Installation contractors	In deployment	**Solution 1.13:** Hygiene and maintenance protocols for vessel hulls and ballast water used by contractors reduces the potential for accidental introduction of invasive exotic marine species (Bennun et al., 2021).	>>> Minimises >>>	**Ecological impact 1.7:** The introduction of nonindigenous species is possibly the most serious risk of both OWF development and nature enhancement therein. Artificial structures in the marine environment are known entry points for settlement of invasive epibiota (Glasby et al., 2007).	
	Research & consultancy	In deployment	See --> **Solution 6.9** (further research into marine ecosystems and OWFs) and **Solution 6.10** (further research into enabling monitoring technologies)	>>> Unknown >>>		

2. Tower and blades: This category contains all ecological impacts and solutions that are centred around the components of wind turbines above water. Including their tower, blades, nacelle and rotor.

When within OWF life cycle to best implement solution	*Stakeholders responsible for solution*	*TRL of solution*	*Solution description*	*Type of mitigation of solution to impact*	*Ecological impact description*	*Receptor of ecological impact*
Site selection		In deployment	See --> **Solution 6.9** (further research into marine ecosystems and OWFs) and **Solution 6.10** (further research into enabling monitoring technologies).	>>> Unknown >>>	**Ecological impact 2.1:** Unknown cumulative influence of blade rotations on wind patterns and sea currents, in the scenario of large scale roll out of OWFs, where the alternation of sea currents may affect all marine life with changing water temperatures and oxygen fluxes (Vrooman et al., 2019).	?
Development		In discovery	**Solution 2.1:** Include seal haul-out platforms on the turbine tower design to provide resting habitat (Stephenson, 2022).	>>> Offsets >>>	**Ecological impact 2.2:** Loss of habitat for some species may be offset by new habitat creation for other species (Stephenson, 2022).	
		In development	**Solution 2.2:** Design turbines to maintain a minimum turbine air gap, which refers to the height between turbine blades and sea level, increases the likelihood of bird passing safely under the turbines and reduces collision risk (Xodus Group & The Rich North Sea, 2024). For instance, SSE Renewables proposes to raise the air gap of Berwick Bank Wind Farm from 22m to 37m above sea level to improve site passage of particularly the kittiwake and guillemot sea birds (SSE Renewables, 2021).	>>> Minimises >>>	**Ecological impact 2.3:** Reduced survival rates and direct mortality caused by collision with spinning turbine blades in the rotor swept zone for migrating and sea-foraging birds and bats (Hammar et al., 2016).	
		In demonstration	**Solution 2.3:** Design turbines to include visual cues, such as high contrast paints schemes, for bird species to better spot spinning blades and stay away (Hermans et al, 2024). For instance, the Norwegian onshore wind farm Smola reduced fatalities of Haliaetus albicilla (White-tailed eagle) by 100% by painting two-thirds of one blade black, as compared to unpainted controls (Bennun et al., 2021).	>>> Minimises >>>		
Construction		In demonstration	**Solution 2.4:** Compensate for bird mortalities by developing OWFS with near shore artificial nesting structures to house sea foraging birds, such as the kittiwake, a vulnerable species of seabird, off the East Suffolk coastline (Ørsted, 2023b).	>>> Offsets >>>		
Operations		In deployment	**Solution 2.5:** Enforce park-wide curtailment for OWFs situated on migratory routes during important migration periods (Hermans et al., 2024). Temporary shutdown during mass migration events to reduce collision risk (especially in bad weather and visibility conditions) has been recommended as mitigation measure. For instance, the German Federal Maritime and Shipping Authority reserves the right to demand shut-downs during mass migration nights (Defingou et al., 2019).	>>> Avoids >>>		
		In demonstration	**Solution 2.6:** Operate turbines with active curtailment based on image detection and radar systems recognising key bird species and shutdown upon approach (GROW, 2023). For instance, OWF Tahkoluoto in Finland deploys Robin Radar Max© which prevents collisions with black-backed gulls and white-tailed sea eagles (Bennun et al., 2021).	>>> Minimises >>>		
		In demonstration	**Solution 2.7:** Operate turbines with curtailment during low wind speeds at dawn and dusk. This minimises bat collision risks because they are most active during this time (Bennun et al., 2021). For instance, Chirotech® is an automated curtailment system based on bat behaviour and real-time environmental data such as temperature, wind and rainfall, to determine when a collision risk threshold is exceeded, to then stop turbine blades from rotating (Bennun et al., 2021).	>>> Minimises >>>		
		In demonstration	**Solution 2.8:** Operate turbines with active deterrence systems, which encourages species to avoid the rotor swept zone (GROW, 2023). For instance, offshore test site Platform FINO in the North Sea, has deployed DTBird®, which is a real-time detection system based on thermal imaging cameras mounted on turbines that activates a warning sound upon recognition of target species such as the golden eagle (Bennun et al., 2021).	>>> Minimises >>>		
		In deployment	To better predict local migration routes intersecting OWFs and adopting curtailment plans accordingly see --> **Solution 6.9** (further research into marine ecosystems and OWFs) and **Solution 6.10** (further research into enabling monitoring technologies).	>>> Unknown >>>		
All stages		In deployment	**Solution 2.9:** Enforce the minimisation of offshore lighting during construction, operation and disassembly (Xodus Group & The Rich North Sea, 2024). For instance, under the OSPAR Convention, North-East Atlantic offshore installations must minimise the number of lights, the intensity of lights and/or adapt the spectrum of lights to a bird-friendly lighting system as much as safely possible (OSPAR Commission, 2015).	>>> Minimises >>>	**Ecological impact 2.4:** Light pollution under poor weather conditions during the night time, attracts migrating land birds, mistaking it offshore infrastructure for land and increasing collision risks. However, a complete switch off of night lights on offshore infrastructures misaligns with maritime safety protocols (Defingou et al., 2019).	
		In deployment	**Solution 2.10:** Stimulate the use of radars systems aboard ships and aircrafts to enable on demand lighting and deflectors on OWFs whenever ship lights project on them (Defingou et al., 2019).	>>> Minimises >>>		

3. Foundation: The foundation of turbines and substations is the below water component. Three types of foundations are fixed to the bottom, and therefore must contain scour protection, which is rock material to withstand seabed erosion. These fixed-bottom foundations include monopiles, jackets, and floating, where the turbine is constructed on a buoyant foundation attached with anchor lines. Some ecological impacts and solutions will only refer to one foundation type. When referred to foundations more generally, a solution applies not only to turbine but any offshore infrastructure for example substation, hydrogen turbine or energy island.



When within OWF life cycle to best implement solution	*Stakeholders responsible for solution*	*TRL of solution*	*Solution description*	*Type of mitigation of solution to impact*	*Ecological impact description*	*Receptor of ecological impact*
Development		In development	**Solution 3.1:** Incorporate passive aquaculture, such as hanging mussel cultures a.k.a. vertical mussel reefs. These can be added as standalone complementary park infrastructure for fixed-bottom foundations, and may potentially be incorporated into the mooring lines of floating wind turbines (Interviewee #1, 2024). A Wageningen Marine Research pilot for dua use aquaculture is running in OWF Borselle (Enter, 2024).	>>> Restores >>>	**Ecological impact 3.1:** Hanging cultures provide a renewable, as opposed to one-time, influx of Calcium carbonate ($CaCO_3$) material the marine ecosystem from shells falling to the seabed. This provides a suitable chemical composition for larval settlement by calcareous organisms such as bivalves thereby stimulating reef creation (DNV and NIVA, 2023) and simultaneously functioning as a food provisioning marine ecosystem service.	
		In demonstration	**Solution 3.2:** Adjust the structure design of monopile foundations to include water replenishment holes where water can exchange from the inside to the outside of the turbine (Ocean Offshore Coalition for Nature and Energy, 2024).	>>> Restores >>>	**Ecological impact 3.2:** Improve internal water quality and provide shelter for macrofauna through allowing access to the internal space of the foundations (GROW, 2023).	
		In demonstration	**Solution 3.3:** Design bottom-fixed foundations, such as monopiles and jacket foundations, with add-on steel gabion cages, such as Biohut® or Witteveen+Bos' Cotel, which can also be added as standalone complementary park infrastructure (Hermans et al., 2020).	>>> Restores >>>	**Ecological impact 3.3:** Increase target species abundance, by providing shelter, nursing and foraging area, for instance, to Atlantic cod. Thereby increasing its biomass and that of associated prey species (Hermans et al., 2020).	
Construction		In development	**Solution 3.4:** Use jetting technology in the construction of monopile turbines, where the seafloor is made fluid so the monopile can slowly be sunk in the seafloor with less sound. This technology is being tested by Ørsted in OWF Gode Wind 3 in Germany, but it may only be suitable for some substrate types and under specific oceanic conditions (Interview #3, 2024; Interview #4, 2024).	>>> Avoids >>>	**Ecological impact 3.4:** Noise pollution arising during the construction of OWFS, particularly in the process of pile driving monopiles into the seabed, harms marine fauna through physical damage, behavioural changes, masking, avoidance and temporary habitat loss (Vrooman et al., 2019).	
		In development	**Solution 3.5:** Apply a combined technology of vibrations on the top of the monopile with jetting inside of the monopile, to reduces resistance, making the installation more efficient and more silent. This technology, named Vibrojet®, was invented by GBM Works and will be tested on three turbines in Hollandse Kust West (HKW) Site VI, in The Netherlands (Voice of Renewables, 2024).	>>> Avoids >>>		
		In development	**Solution 3.6:** Use the weight of a massive water column, in combination with gas combustion to pile a monopile into the seabed. This quieter technology is called blue piling (Bennun et al., 2021).	>>> Minimises >>>		
		In demonstration	**Solution 3.7:** Hydro sound damper (HSD) methods involve surrounding the pile with foam plastic elements or gas-filled balloons that absorb and reflect sound (Renewables Grid Initiative, 2024).	>>> Minimises >>>		

		In deployment	**Solution 3.8:** Generate an air bubble curtain by placing a hose pressurised by air compressors on the seafloor in a loop around a monopile installation as a means of noise abatement (Leander Vølstad et al., 2022; Tsouvalas et al., 2016).	>>> Minimises >>>		
		In deployment	**Solution 3.9:** Use Acoustic Deterrent Devices (ADDs) to chase away marine fauna from the impact area prior to commencing in noisy construction activities. Then monitor for key species to stay clear of this safety zones throughout the construction process (McGarry et al., 2022).	>>> Minimises >>>		
		In deployment	**Solution 3.10:** Place cofferdams, which are single-walled steel tube casings, to evacuate the water and the pile inserted so the piling noise is reflected (Renewables Grid Initiative, 2024).	>>> Minimises >>>		
		In deployment	**Solution 3.11:** Instigate threshold values for developers to adhere to during the foundation construction processes in particular, and furthermore into relation to boating traffic throughout the operation (Defingou et al,. 2019).	>>> Minimises >>>		
		In deployment	**Solution 3.12:** Encourage innovative quite installation methods through non-price tender criteria (DNV and NIVA, 2023).	>>> Minimises >>>		
		In deployment	See --> **Solution 1.9** (allocate construction zones and don't deviate works outside of them).	>>> Minimises >>>	**Ecological impact 3.5:** Construction of bottom-fixed foundations causes turbidity and sediment dispersal to the seabed and can thereby indirectly impair some benthic species or make them more susceptible to predation (Defingou et al., 2019).	
		In discovery	To some extent unavoidable, thus see **Solution 6.8** (Biodiversity offsetting).	>>> Offsets >>>		
		In demonstration	See --> Any habitat restoration solution, for example **Solution 4.1** (Additional boulders in scour protection) or **Solution 4.2** (Adapted armour layer in scour protection).	>>> Restores >>>	**Ecological impact 3.6:** Habitat loss underneath foundation: For monopiles, and to a lesser extent jacket and floating turbines, some habitat loss occurs directly underneath their foundations, however the total area lost is relatively small (Bennun et al., 2021).	
Operations		In deployment	See --> **Solution 3.9** (Use Acoustic Deterrent Devices).	>>> Minimises >>>	**Ecological impact 3.7:** The large scale roll out of floating turbines may pose an increased risk of entanglement for marine megafauna or disrupt their ability to navigate.	
		In deployment	See **Solution 6.9** (further research into marine ecosystems and OWFs) and **Solution 6.10** (further research into enabling monitoring technologies).	>>> Unknown >>>		
		In deployment		>>> Unknown >>>	**Ecological impact 3.8:** The mooring lines of floating turbines are not taut lines, but rather have some suspension on them to prevent tension when moving (Al-Solihat and Nahon, 2016). When there is a lot of slack on the mooring lines they may be scraping over the seabed and disturbing the prevailing benthos and possibly causing noise pollution.	
		In deployment		>>> Unknown >>>	**Ecological impact 3.9:** Toxic effects on marine organisms, and through bioaccumulation the food web at large, caused by the gradual release of antifouling chemicals from antifouling paints used on foundation and cables (Interview #6, 2024).	?
Decommissioning		In discovery	**Solution 3.13:** On a case by case basis consider allowing for leaving infrastructure in place if there is a biodiversity/ecosystem services benefit such as the reef effect (DNV and NIVA, 2023). For example the Bureau of Safety and Environmental Enforcement's Rigs-to-Reefs aims to develop national policy to recognise artificial reef benefits of oil and gas platforms.	>>> Avoids >>>	**Ecological impact 3.10:** Currently, marine artificial structures must be completely removed at end-of-life according to the majority of international, regional and national legislation (Knights et al., 2024b). However, there effect of OWF decommissioning on the marine environment is largely unknown (Eckardt et al, 2022.) but likely destroys the artificial reef habitats and associated biomass that has accumulated in an OWF over its lifetime of 20 to 25 years.	
		In discovery	**Solution 3.14:** Scour protection must be left intact and on foundation structures that don't have scour protection it's recommended to cut the foundation above the seabed instead of at the base (Spielmann et al., 2023).	>>> Minimises >>>		
		In discovery	**Solution 3.15:** If there is no chance of leaving the novel marine habitats that have evolved on scour protection and foundations, an alternative solution may be to relocate the ecologically valuable material to a new OWF location or nature reserve. Relocated novel habitat to the a new OWF location or nature reserve (Interview #1, 2024).	>>> Restores >>>		
		In discovery	See --> **Solution 3.9** (Use Acoustic Deterrent Devices) and **Solution 3.8** (use bubble curtains).	>>> Minimises >>>	**Ecological impact 3.11:** Noise pollution arising during the disassembly of turbine foundations at end of life, harms marine fauna through physical damage, behavioural changes, masking, avoidance and temporary habitat loss (Vrooman et al., 2019).	

4. Scour and cable protection: This refers to the base case scour protection, which is required to prevent seabed erosion, for bottom-fixed turbines, substations and complementary OWF infrastructure, such as a co-located offshore hydrogen facility. It also includes the base case protection infrastructure required for array and export cables and cable crossings.

When within OWF life cycle to best implement solution	*Stakeholders responsible for solution*	*TRL of solution*	*Solution description*	*Type of mitigation of solution to impact*	*Ecological impact description*	*Receptor of ecological impact*
Development		In demonstration	**Solution 4.1:** Adding additional calcareous boulders and rocks of heterogeneous sizes and shapes, with adjusted grading of e.g. 40-200 kg, to the standard scour or cable protection (Hermans et al., 2020; Interviewee #1, 2024; Interviewee #4, 2024; Interviewee #5, 2024; Interviewee #6, 2024).	>>> Restores >>>	See --> **Ecological impact 3.3** (Increasing biomass of target species and associated prey species). Additionally, **Ecological impact 4.1:** Supporting prey-predator interactions by providing hard substrate for epibenthic species on the surface, leading to an overall increase in biomass (Hermans et al., 2020).	
		In demonstration	**Solution 4.2:** Adapting the existing scour protection armour layer to contain crevices minimum of 10 cm to a maximum of 30 cm in diameter and a minimum of 20 cm to a maximum of 50 cm deep (Hermans et al., 2020).	>>> Restores >>>		
		In development	**Solution 4.3:** Add mesh nets filled with Quarry rock or basalt with a well sorted grading of 40-200 kg. Lay on top of scour protection, cable protection or cable crossings (Hermans et al., 2020).	>>> Restores >>>		
		In development	**Solution 4.4:** Replace regular turbine scour protection by fully structural, interlocking, ecological concrete units that are gravity fed from a barge. For example ECOncrete® Wind Turbine Scour Protection Units, which are made of unit designs and surface textures that mimic features naturally found in marine environments (The Nature Conservancy and INSPIRE Environmental, 2021).	>>> Restores >>>	See --> **Ecological impact 3.3** (Increasing biomass of target species and associated prey species). Additionally, **Ecological impact 4.2:** Decrease domination of invasive species and improve water quality (The Nature Conservancy and INSPIRE Environmental, 2021).	
		In development	**Solution 4.5:** Replace regular turbine scour protection by anti-scour frond mattresses, such as the SPS Frond Mattress. This consists of over 1000 buoyant fronds per square metre at nominally one metre high, built into a matrass structure at the foot of a jacket foundation. This structure replicates the natural phenomenon of natural seaweed reducing water velocity and correspondingly reducing seabed erosion (SPS Concrete Specialists, 2024).	>>> Restores >>>	See --> **Ecological impact 3.3** (Increasing biomass of target species and associated prey species).	
		In development	**Solution 4.6:** Cover cables with flexible mat-type protection structures such as Reef cube® matt™, Fleximats® and Marine matt®. Such mats are typically constructed of high-strength concrete profiled blocks providing structural complexity and tied together with ultraviolet-stabilized polypropylene rope (The Nature Conservancy and INSPIRE Environmental, 2021).	>>> Restores >>>	**Ecological impact 4.3:** Encourage faster colonisation of benthic epifauna (The Nature Conservancy and INSPIRE Environmental, 2021) in turn providing nutrients for benthic species such as edible crabs and European lobsters increasing their biomass (Hermans et al., 2020).	
		In deployment	**Solution 4.7:** Routing array and export cables most appropriately, length efficiently and away from sensitive areas (Hermans et al., 2024).	>>> Avoids >>>	**Ecological impact 4.4:** Minimise the disturbance of magnetic and electromagnetic fields and heat emission of electricity cables to marine species. Such as disruption of cartilaginous fish in detecting prey, for which they use electromagnetic signals (Kimber et al, 2011). And the disrupted migration patterns of marine mammals and fish, which orientate in relation to the geomagnetic field (Westerberg and Lagenfelt, 2008).	
Construction		In deployment	**Solution 4.8:** Shield and bury cables at an adequate depth. For example the BSH Federal Maritime and Shipping Authority (BSH) requires for cables to be buries such that heating of the sediment does not exceed 2 K at 30 cm depth (Defingou et al., 2019).	>>> Minimises >>>		
		In discovery	Solution 4.9: Add repurposed materials that have previously been submerged into seawater, to either the scour or cable protection or as standalone structures. For example, concrete from bridges (The Nature Conservancy and INSPIRE Environmental, 2021).	>>> Restores >>>	See --> **Ecological impact 3.3** (Increasing biomass of target species and associated prey species) and **Ecological impact 4.1** (Providing hard substrate for epibenthic species to settle). Additionally, **Ecological impact 4.5:** the emission of CO2 from newly manufactured materials is substituted by sequestered CO2 of repurposed materials (The Nature Conservancy and INSPIRE Environmental, 2021).	
		In demonstration	**Solution 4.10:** Place oyster gabions directly on top of scour protection. These net cages have a mesh size no smaller than 5x5cm which prevent oyster shells from falling out (Hermans et al., 2020).	>>> Restores >>>	See --> **Ecological impact 3.1** (influx of Calcium carbonate ($CaCO_3$) material the marine ecosystem). Additionally, **Ecological impact 4.6:** Encourage faster colonisation of reef building species (European flat oyster) by providing hard substrate; simultaneously providing habitat for juvenile fish and small epibenthic species (Hermans et al., 2020).	

	When within OWF life cycle to best implement solution	Stakeholders responsible for solution	TRL of solution	Solution description	Type of mitigation of solution to impact	Ecological impact description	Receptor of ecological impact
	Operations		In demonstration	**Solution 4.11:** Adding reef-stimulating natural materials such as shells, gravel or BESE-reef paste into the scour protection, cable protection or cable crossings (*Bureau Waardenburg, 2020*).	>>> Restores >>>	See --> **Ecological impact 3.1** (influx of Calcium carbonate ($CaCO_3$) material the marine ecosystem), except this is a one-off instead of a sustainable influx.	
			In demonstration	**Solution 4.12:** Remote settling of spat. This process involves initial growing of larvae in a contained lab environment onto material to be used as scour protection, cable protection or cable crossings. Once young oysters have settled onto rock material, it is outplaced to the open sea environment amongst other rock material used in the scour protection (Interviewee #1, 2024; Interviewee #6, 2024).	>>> Restores >>>	**Ecological impact 4.7:** Reintroduce ecologically degraded reef building species, such as the European flat oyster, consequently enhancing the creation of biogenic reef structures which stimulates overall biodiversity and productivity of marine ecosystems (Sas et al., 2023).	

5. Complementary infrastructure: This category includes ecological impacts and their solutions that can be found on additional infrastructure of an OWF that is not part of its base case design, but rather includes infrastructure required for dual-use purposes (such as aquaculture and nature protection) or co-location of renewables (such as offshore hydrogen and floating solar power).

	When within OWF life cycle to best implement solution	Stakeholders responsible for solution	TRL of solution	Solution description	Type of mitigation of solution to impact	Ecological impact description	Receptor of ecological impact
	Operations		In development	**Solution 5.1:** Rewild life adult reef building species, such as the European flat oyster to biodegradable artificial structures that slowly decompose to leave individuals to gradually attach to natural hard substrate (ARK Rewilding Nederland, 2024).	>>> Restores >>>	See --> **Ecological impact 4.7** (Reintroduce degraded reef building species).	
			In demonstration	**Solution 5.2:** Place broodstock basket structures between turbines, that can be lifted in and out of the water to evaluate success. For instance, the WERC-dock is a robust device which holds oyster baskets on three layers over a fixed pole. The baskets can be collected with an ROV to monitor restoration parameters, such as survival, growth, reproduction and recruitment, without the need for a diver to enter the water (Bos et al., 2023).	>>> Restores >>>		
			In demonstration	**Solution 5.3:** Place broodstock tables near turbines. These tables contain vertical columns that each have dozens of adult oysters securely attached (not caged in). When they spawn, larvae settle on surrounding hard substrate, such as the scour or cable protection (Schonebeek, 2023).	>>> Restores >>>		
			In development	**Solution 5.4:** Place biodegradable artificial reef structures as standalone units in between turbines. For instance, NIOZ's Treef (Tree-reef), consists of a concrete base stabilising pear tree wood material atop (The Rich North Sea, 2024) and Van Oord's GEOWALL® reef blocks are composed of compressed dredging sludge (Geowall, 2024).	>>> Restores >>>	See --> **Ecological impact 3.3** (Increasing biomass of target species and associated prey species) and **Ecological impact 4.1** (Providing hard substrate for epibenthic species to settle).	
			In deployment	**Solution 5.5:** Place large artificial reef structures as standalone units in between the turbines. Examples include Cod Pipe Reef, Reef Cubes®, SeaCult Reef System or simply unbranded drainage pipes of varying sizes or other large concrete chunks with holes, crevices and varying forms (Lengkeek et al., 2017).	>>> Restores >>>		
			In deployment	**Solution 5.6:** Place small 3D printed artificial reef structures as standalone units in between turbines. Examples include Reef Balls®, Layer Cakes, Reef cube®, ECO Armour Block®, Cube Reefs, Reef Cells (Hermans et al., 2020). Here the shape, texture and jaggedness of the units is more customisable than for large artificial reef structures, but produced at a higher per unit cost.	>>> Restores >>>		
			In deployment	See --> **Solution 6.9** (further research into marine ecosystems and OWFs) and **Solution 6.10** (further research into enabling monitoring technologies).	>>> Unknown >>>	**Ecological impact 5.1** Loss of plankton biomass and mortality of macrofauna due to large quantities of water extraction required in desalination (352m3/hour) and cooling (26000m3/hour) processes of offshore hydrogen energy production (Witteveen+Bos, 2024).	?
					>>> Unknown >>>	**Ecological impact 5.2:** Toxic effects on marine organisms, and through bioaccumulation the food web at large, caused by the release of antifouling chemicals in discharge water of offshore hydrogen cooling systems (Interviewee #6, 2024).	
					>>> Unknown >>>	Ecological impact 5.3: Direct (e.g. disturbance) and indirect (e.g. water turbulence, salinity, turbidity, stratification effects) ecological effects of emission of seawater with increased salinity (1.3‰) of offshore hydrogen plant (Witteveen+Bos, 2024).	
					>>> Unknown >>>	**Ecological impact 5.4:** Harm caused by noise pollution, thereby most likely impacting marine mammals) from offshore hydrogen installations' pumps, fans and compressors (Interviewee #4, 2024).	
					>>> Unknown >>>	**Ecological impact 5.5:** Direct (e.g. decreased survival rates, attraction of invasive species) and indirect (e.g. hydrodynamic changes like stratification and destratification) ecological effects of emission of seawater with increased temperature (+5 degrees Celsius) of offshore hydrogen plans (Interviewee #4, 2024).	
					>>> Unknown >>>	**Ecological impact 5.6:** Deficit of light penetrating water when floating solar panels are deployed at large scale, decreases primary productivity and surface water temperature and modifies waves, currents and stratification (Karpouzoglou et al, 2020; Rocha et al., 2024), which may influence marine organisms in myriad ways.	

6. Outside of OWF: Includes solutions and ecological impacts that are either, not under the direct mandate of OWF developers, or don't exist in the direct vicinity of an OWF, but are indeed inherently related to the healthy functioning of marine ecosystems in OWFs.

	When within OWF life cycle to best implement solution	Stakeholders responsible for solution	TRL of solution	Solution description	Type of mitigation of solution to impact	Ecological impact description	Receptor of ecological impact
	Development		In deployment	**Solution 6.1:** Install flight diverter devices such as flappers, balls or spirals to increase the visibility of transmission lines (Bennun et al., 2021).	>>> Minimises >>>	See -> **Ecological impact 2.3** (Reduced survival rates of avian species due to collision), except cause of collision is not with turbine blades but with onshore overhead powerlines associated with OWF connection to the grid (Bennun et al., 2021).	
			In demonstration	**Solution 6.2:** Design wildlife-safe or retrofitting overhead wires and poles, to reduce electrocution risk from contact (Bennun et al., 2021).	>>> Minimises >>>		
			In deployment	**Solution 6.3:** Reduce collision risk by altering the transmission line configurations, by either decreasing the span length or the vertical spread of the lines (Bennun et al., 2021).	>>> Minimises >>>		
			In demonstration	**Solution 6.4:** Use non-price criteria in the tender of an offshore wind lot to reward OWF projects enhancing coexistence between species and with other economic sectors (e.g. organic agriculture or mussel farms) (DNV and NIVA, 2023).	>>> Restores >>>	**Ecological impact 6.1:** Harmful fishing practicing such as bottom-trawling or overfishing, in the direct vicinity of OWFs, directly pressures the fish populations recovering at the bases of turbine foundations and standalone artificial reefs, thereby threatening ecosystem functioning and lower trophic guilds (Bennun et al., 2021).	
	Operations		In development	**Solution 6.5:** Appoint and enforce a Marine Protected Area (MPA), No Take Zone (NTZ), or other regulatory status to the OWF site, to prohibit bottom disturbing fishing practices such as trawling entirely (Interviewee #5, 2024).	>>> Avoids >>>		
	All stages		In deployment	**Solution 6.6:** Enforce strict catch quotas to regulate fishing practicing in between turbines and near OWFs (DNV and NIVA, 2023).	>>> Minimises >>>		
			In demonstration	**Solution 6.7:** Encourage and subsidise passive fisheries methods, such as handline, jigging, gill netting and the use of pots and traps or aquaculture, such as shell fish and seaweed farming in the direct vicinity of OWFs, as a means of discouraging bottom-trawling (Visserij Nieuws, 2023).	>>> Minimises >>>		
			In development	**Solution 6.8:** Biodiversity offsetting, which is the quantification of the unmitigable ecological impact and funding a conservation or restoration effort of this same proportion elsewhere into a so-called receptor site, is uncommon practice within the OWF sector. However to reach a net zero or net positive impact on the environment as many developers claim to be committed to, biodiversity offsetting must be resorted to for any of the negative ecological impacts that cannot fully be eliminated for an OWF to exist. For instance, some bird mortality from collision with blades, is unpreventable by the inherent presence of wind turbines. Therefore, biodiversity offsetting for these losses to the bird population, could take the form of financing the protection of important onshore breeding areas outside of the OWF itself, possibly even through a centrally managed government fund (Interview #3, 2024).	>>> Offsets >>>	See --> all ecological impacts that do not contain a mitigation solution to avoid them. These require some offsetting to achieve net zero impact.	

			In deployment	**Solution 6.9:** Stimulate, fund or conduct further research into specific issues surrounding marine ecosystems and OWFs. For the study of marine ecosystems in OWFs generally there is a need for focus on large-scale effects, through hypothesis-driven research at smaller scales complemented modelling approaches to upscale potential ecological changes (Wilding et al., 2017). To determine the potential changes induces by OWFs, detailed spatio-temporal insight is required of the natural variability of benthic systems (Dannheim et al., 2020). For instance, Marine Scotland launched a research project named 'Cumulative Effects Framework for Key Ecological Receptors', which aims to develop a framework for assessing impacts of all offshore installations on sea birds and marine mammals, over multiple years and at multiple population scales, to be able to predict ecological impacts at a population level for individual projects and cumulative assessments (Leander Vølstad et al., 2022).	**>>> Unknown >>>**	See --> all ecological impacts of which the mitigation solution is unknown.	?
			In deployment	**Solution 6.10:** Stimulate, fund or conduct further research into enabling monitoring technologies to advance data collection in the tough field conditions of submerged OWF territory. Such bluetech technologies include cutting-edge sensors and submersible drone, real-time measurement systems and machine learning models and robotics systems for data processing and analysis (SeaAhead, 2024; Hoekendijk, 2024).	**>>> Unknown >>>**		

4.1.3. Foundation

With the placement of OWF infrastructure, the local marine habitat simultaneously diminishes and increases (Langhamer, 2012). For fixed-bottom turbines, habitat loss occurs directly underneath their foundations, so the total area lost is relatively small (Bennun et al., 2021). The rise of the floating turbine, anchored to the seabed by three to five mooring lines, comes with the expectation of further minimised habitat loss, for only a few square meters per turbine is required for installation of anchors (SEER, 2022). Floating turbines can be employed in much deeper waters than their fixed-bottom counterparts which typically have a maximum depth ranging from 40 to 60 meters (Praya and Zigeng Du, 2020). Depending on gravity of the foundation construction works, the total area of benthic habitat destruction varies. This is detailed in the third section, named *Foundation.* Where some solutions and ecological impacts will only refer to fixed-bottom and other only to floating foundations.

Where vessel traffic and operational noise, originating from the vibrations of the gearbox meshing the electricity generator, have limited environmental impact beyond the vicinity of each turbine (Hammar et al., 2010). However, monopile and jacket foundations require the noise-heavy process of piledriving. During the construction of such turbine's foundation, acoustic disturbance can cause auditory injury and behavioural changes such as avoidance (Vrooman et al., 2019). Gravity foundations are deployed through drilling and dredging activities which are quieter (Bergström et al., 2014) and floating turbines avoid noise pollution further, requiring only attachment of anchor systems into the seabed. The *Foundation* section describes the many noise mitigation measures that can be undertaken during construction, such as the usage of bubble curtails and Acoustic Deterrent Devices (ADDs) (Renewables Grid Initiative, 2024). Or, foresight to time construction and disassembly activities outside of sensitive migration and spawning periods. Hammar (2014) illustrates the example that the acoustic disturbance of pile-driving can endanger species significantly more in their spawning or nursing periods. Instead of minimising noise impacts, newer technologies focus on preventing the source of the noise impact by testing alternative installation methods. For instance jetting is the processing of fluidising the seafloor to slowly and silently sink monopiles in (Voice of Renewables, 2024).

4.1.4. Scour and cable protection

The fourth section, *Scour and cable protection,* refers to the base case material needed to protection turbines and cables from seabed erosion. Inherently, scour and cable protection provide hard substrate for benthic species to colonise and fishes to feed on (The Nature Conservancy and INSPIRE Environmental, 2021). It can also function as shelter, nursery and reproduction grounds for many fish species (Glarou et al., 2020). A mash of boulders and rocks of various sizes creates crevices which offer hiding opportunities for fish and other fauna, similarly to the protective workings of a natural reef (Beisiegel et al., 2019). As such, artificial structures like turbine foundations and their scour protection increases biological heterogeneity through growing species diversity and density (Langhamer, 2012). Where increased biological diversity is seen as a positive change in many (depleted) marine ecosystems, scour protection has been investigated for optimal habitat creation to amplify its reef effect (Hammar er al, 2010). Adding as much rock dump in various sizes around the foundation of a turbine (Coolen et al., 2018) increases its the structural complexity. Besides the novel ecosystems unfolding at the base of turbine foundations, a second distinct artificial habitat extends vertically. Through the water column from the seafloor up to the splash zone in open sea where otherwise comparable natural hard substrate of this kind does not exist (Degraer et al., 2020), but rather reflecting rocky shore communities' zonation patterns (Langhamer, 2012). Near the water surface mussels, macroalgae and barnacles dominate the biotic community of a wind turbine, whilst filter-feeding arthropod colonise at intermediate depths and in the benthic zone anemones dominate (Degraer et al., 2020). The organic matter filtered from the water column, enters the food availability as suspension feeders are preyed on. Their fecal deposits too contribute to seafloor communities, thereby supplying higher and lower trophic levels with surplus energy (SEER, 2022).

The Nature Conservancy & INSPIRE Environmental (2021) point out the distinguishment between *scour enhancement* and *scour material*, where the former refers to the structural complexity (the sizes and shapes) of the selected scour layer. And the later, scour material, refers to the selection of concrete or steel product that is most suitable to the ecosystems. For example, repurposing decommissioned concrete of a bridge structure, which has already been submerged in seawater for decades, is not only cost-effective, but also demonstrates high success rates as artificial reef material. Furthermore, mixing Calcium carbonate ($CaCO_3$) or natural shells into the concrete structures can create a suitable chemical composition for larval settlement of calcareous organisms, like bivalves (The Nature Conservancy & INSPIRE Environmental, 2021).

Magnetic and electromagnetic fields of OWFs potentially also pose a threat to marine mammals and fish (Westerberg and Lagenfelt, 2008). Electricity cables, placed on the sea floor to transmit the wind-generated energy ashore, are cased in magnetic fields. This can induce electric fields in moving water (Gill et al., 2012) and disrupts cartilaginous fish in detecting prey, for which they use electromagnetic signals (Kimber et al., 2011). The *Scour and cable protection* section also includes the protection infrastructure required for array and export cables and cable crossings. Marine mammals and fish are disrupted in their migration patterns by the electromagnetic fields of OWFs' cables. It interferes with their ability to orientate in relation to the geomagnetic field (Westerberg and Lagenfelt, 2008). Nevertheless, the chronic and long-term effects of anthropogenic underwater noise, magnetic fields and electromagnetic fields on marine mammals are yet to be studied. Clear evidence of the implications of the avoidant behaviour remains poor (Jhan et al., 2022).

4.1.5. Complementary infrastructure

The fifth section, *Complementary infrastructure,* includes ecological impacts and their solutions that can be found on additional infrastructure of an OWF that is not part of its base case design. This is either standalone units to make an OWF dual use with aquaculture or nature enhancement. Artificial reef units of various shapes and sizes mimic naturally occurring complex habitat features and thereby shelter bottom-associated species (DNV and NIVA, 2023) and functioning as habitat restoration. Components that are not part of the base case build, can also refer to infrastructure required for co-location of renewables. Both floating solar and offshore hydrogen power production have several very concerning and understudied outcomes for the marine ecosystem, as laid out in the *Complementary infrastructure*.

4.1.6. Outside of OWF

Sixth and final section, *Outside of OWF,* describes actions that can be taken to directly influence the healthy functioning of marine ecosystems in OWFs, but are either, not under the direct mandate of OWF developers, or don't exist in the direct vicinity of an OWF. The regulation of harmful fishing methods and promotion of sustainable, passive fishing methods are described here. This section also provides in-depth descriptions of biological offsetting which referred to throughout all other sections. As well as the further research that is required into both the ecology in OWFs and the enabling monitoring technologies required to do so. Furthermore, bird mortality associated with the operation of offshore wind energy production takes place outside of the OWF boundary, on land. Birds and bats can be electrocuted by overground transmission lines, usually on the pylons of low- and medium voltage lines, when mistaken for hunting or nesting perches (Bennun et al., 2021).

4.2 Existing, upcoming and missing solution to ecological impacts of OWFs

The next sections will point out overarching trends from the nature inclusivity framework (table 4), by looking at two different summative representations of it: The visual infographic (figure 6) and the tabular summary (table 5) classifying ecological impacts of OWFs and their solutions, by mitigation hierarchy and TRL. Using these, the section below aims to describe, according to this study's framework, which solutions are existing, upcoming and missing.

Firstly, existing solutions are the ones with a TRL of *in deployment*, meaning they are on-market and fully operational (Rijksdienst voor Ondernemend Nederland, 2022). An important caveat to this definition being that a solution may have advanced into operational status in one area. Yet simultaneously it is not yet frequently implemented elsewhere in the world. For instance, non-price criteria to stimulate ecological functioning are well integrated in Dutch tenders, and only starting up in other countries (Renewables Grid Initiative, 2024). Nevertheless, the solutions that are known to be *in deployment* (figure 6) include numerous noise reduction techniques for pile driving turbine foundations, including Acoustic Deterrent Devices (ADDs), bubble curtains and cofferdams. Also existing, in terms of avoiding collision risks for avian species, is curtailment based on mass migration, minimising offshore lighting and altering onshore line configurations. Existing, i.e. *in deployment*, in the complementary infrastructure section, are both small and large artificial reef units of various shapes and sizes. To mimic naturally occurring complex habitat features and thereby shelter bottom-associated species (The Nature Conservancy and INSPIRE Environmental, 2021). However, these solutions do not prevent or minimise habitat destruction, but fulfil a restorative function, which in the mitigation hierarchy is subordinate to avoiding and minimising ecological impact. Importantly, the most effective existing, in deployment solutions are the ones that avoid ecological impact entirely. These include placing turbines and routing cables outside of ecologically valuable areas, both in the site allocation and during micrositing. All solutions that *avoid* an ecological impact in the first place (at the top in table 5), are vital in facilitating nature inclusivity in OWFs. Especially the solutions that already exist or are in development.

Solutions that have a TRL of *in demonstration* or *in development* can be considered upcoming. To recap the definitions used by the Rijksdienst voor Ondernemend Nederland (2022), *in development* means proof-of-concepts of the innovation are in development and prototypes tested in pilot environments. The *in demonstration* phase follows, when prototypes of the innovation are demonstrated in operational environments for practical insights and practice its market compatibility (Rijksdienst voor Ondernemend Nederland, 2022). It appears that upcoming solutions are being developed and demonstrated across all spatial aspects of OWFs (figure 6). In *Tower and blades* various curtailing methods as well as paint schemes aim to minimise avian mortalities. Within the construction of fixed-bottom foundations, installation methods are underway that absorb pile driving sound, such as blue piling and Hydro Sound Dampers (HSD) (Renewables Grid Initiative, 2024). As well as foundation installation techniques that do not produce sound in the first place, such as jetting and Vibrojet® (Voice of Renewables, 2024). Thereby they *avoid* the acoustic disturbance to marine mammal and fishes, which is preferrable over *minimising* this ecological impact.

At the seabed, many innovations are *in development* suitable for either direct placement onto scour and cable protection or as standalone structures, to function as shelter and nursery grounds for target species and hard substrate for benthic organisms to settle on (Hermans et al., 2020). Examples include mesh nets filled with quarry rock with a well sorted grading and mess size, ECOncrete® Scour Protection Units, anti-scour frond mattresses, flexible matrasses with complex surface on top of cable protection (Hermans et al., 2020). Ultimately adding heterogeneous calcareous rocks on top of scour protection or adapting the armour layer of scour protection to contain heterogeneous calcareous rocks, fulfils the same ecological function of restoring habitat (Ter Hofstede et al., 2023). An optimised scour protection layer with larger rock grading to create a varying size of crevices to accommodate different life stages of target species (Hermans et al., 2020). Importantly, there are already on-market solutions that address this ecological impact. This cannot be said for, reintroducing reef-building species and artificially increasing the influx of $CaCO_3$ into ecosystem, which supports reef-builders (DNV and NIVA, 2023). This is an area of OWF nature enhancement that is still strongly in development. It includes solutions like placing broodstock structures (Bos et al., 2023), remote settling spat onto scour protection and hanging mussel cultures in OWFs (Enter, 2024).

Finally, some solutions have been identified, but remain in the TRL realm of *in discovery.* This means the fundamental concepts and applications of an innovation (i.e. nature inclusivity solution) are being researched and better understood (Rijksdienst voor Ondernemend Nederland, 2022). A number of *in discovery* solutions are clustered together each relating to disassembly of turbines (foundation section of figure 6). Uncertainty remains around the fate of the artificial reef habitats and associated biodiversity that an OWF has fostered, once after 20 to 25 years it is to be decommissioned (Eckardt et al., 2022). Currently, marine artificial structures must be completely removed at end-of-life according to most international, regional and national legislation (Knights et al., 2024). However, there effect of OWF decommissioning on the marine environment is largely unknown (Eckardt et al., 2022), as per the early 2020s only six small, near-shore shallow water OWFs have been decommissioned (Herzig, 2022). To benefit the novel marine life inhabiting turbine infrastructure, scour protection must be left intact (Spielmann et al, 2023). For foundation types that don't require scour protection, it's recommended to cut the foundation above the seabed instead of at the base (Spielmann et al., 2023). Ultimately the appropriate extent of artificial structure removal in the decommissioning stage should be determined case-by-case. It depends on the trophic linkages, habitat provision, population size and stability provided in the population dynamics that OWFs bring to a marine environment (Knights et al., 2024b).

Figure 6. Infographic of nature inclusivity in OWFs: Solutions to implement in design and planning of OWFs to mitigate impacts to the marine ecosystem.

This infographic serves as a visual companion to the framework on nature inclusivity in OWFs, found in table 4. As in table 4, mitigation solutions are grouped into the spatial categories: *1) Layout and location*, *2) Tower and blades*, *3) Foundation*, *4) Scour and cable protection*, *5) Complementary infrastructure* and *6) Outside of OWF*. Solutions are numbered in accordance with table 4 and highlighted into their respective Technological Readiness Level (TRL): *In discovery*, *In development*, *In demonstration* or *In deployment*. The ecological impacts of OWFs are grouped separately into the receptors of their disruption, which can overlap. These receptors categories are adapted from Vrooman et al (2019) include: *Birds*, *Bats*, *Marine mammals*, *Fish*, *Benthic species*, *Multiple trophic guilds* and *Unclear*. As with the solutions, the ecological impacts are numbered in accordance with the full framework in table 4. They are colored by the highest possible mitigation status of one of its respective solutions, using the Mitigation Hierarchy categories adapted from Bennun et al (2021): *Avoid*, *Minimise*, *Restore*, *Offset* and *Unknown*. Refer to table 4 for the full overview of relationships between ecological impacts of OWFs and their solutions.

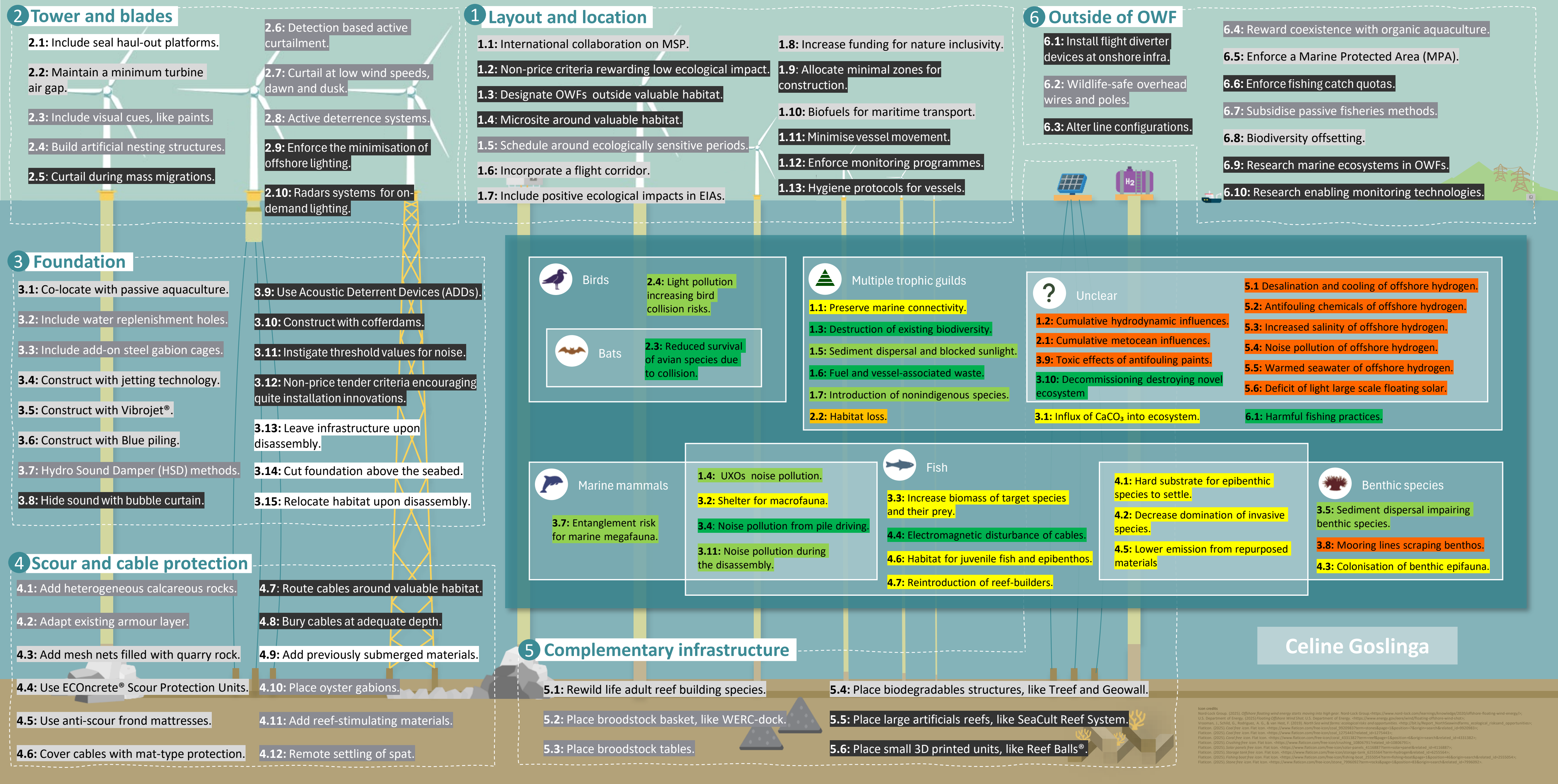


Table 5. A summary of the existing, upcoming and missing solutions to implement in OWF design and planning to conserve marine ecosystems

>>> Avoids >>>		
TRL of solution	*Solution description*	*Ecological impact description*
In deployment	**Solution 1.2:** Non-price criteria rewarding low ecological impact.	**Ecological impact 1.3:** Destruction of existing biodiversity.
	Solution 1.3: Designate OWFs outside valuable habitat.	
	Solution 1.4: Microsite around valuable habitat.	
	Solution 2.5: Curtail during mass migrations .	**Ecological impact 2.3:** Reduced survival of avian species due to collision.
	Solution 4.7: Route cables around valuable habitat.	**Ecological impact 4.4:** Electromagnetic disturbance of cables.
In demonstration	**Solution 1.5:** Schedule around ecologically sensitive periods.	See --> **Ecological impact 1.3:** Destruction of existing biodiversity.
In development	**Solution 1.10:** Biofuels for maritime transport.	**Ecological impact 1.6:** Fuel and vessel-associated waste.
	Solution 3.4: Construct with jetting technology.	**Ecological impact 3.4:** Noise pollution from pile driving.
	Solution 3.5: Construct with Vibrojet®.	
	Solution 6.5: Enforce a Marine Protected Area (MPA).	**Ecological impact 6.1:** Harmful fishing like bottom-trawling or overfishing
In discovery	**Solution 3.13:** Leave infrastructure upon disassembly.	**Ecological impact 3.10:** Decommissioning destroying novel ecosystem.
>>> Minimises >>>		
TRL of solution	*Solution description*	*Ecological impact description*
In deployment	**Solution 1.9:** Allocate minimal zones for construction.	**Ecological impact 1.5:** Sediment dispersal and blocked sunlight.
	Solution 3.9: Use Acoustic Deterrent Devices (ADDs).	**Ecological impact 1.4:** UXOs noise pollution.
	Solution 1.11: Minimise vessel movement.	See --> **Ecological impact 1.6:** Fuel and vessel-associated waste.
	Solution 1.12: Enforce monitoring programmes.	See --> All ecological impacts with a restoration mitigation solution.
	Solution 1.13: Hygiene protocols for vessels.	**Ecological impact 1.7:** Introduction of nonindigenous species.
	Solution 2.9: Enforce the minimisation of offshore lighting.	**Ecological impact 2.4:** Light pollution increasing bird collision risks.
	Solution 2.10: Radars systems for on-demand lighting.	
	Solution 3.8: Hide sound with bubble curtain.	See --> **Ecological impact 3.4:** Noise pollution from pile driving.
	See --> **Solution 3.9:** Use Acoustic Deterrent Devices.	
	Solution 3.10: Construct with cofferdams.	
	Solution 3.11: Instigate threshold values for noise.	
	Solution 3.12: Non-price tender criteria encouraging quite installation innovations.	
	See --> **Solution 1.9:** Allocate minimal zones for construction.	**Ecological impact 3.5:** Sediment dispersal impairing benthic species.
	See --> **Solution 3.9:** Use Acoustic Deterrent Devices.	**Ecological impact 3.7:** Entanglement risk for marine megafauna.
	Solution 4.8: Bury cables at adequate depth.	See --> **Ecological impact 4.4**: Electromagnetic disturbance of cables.
	Solution 6.1: Install flight diverter devices at onshore infra.	See -> **Ecological impact 2.3:** Reduced survival of avian species due to collision.
	Solution 6.3: Alter line configurations.	
	Solution 6.6: Enforce fishing catch quotas.	See --> **Ecological impact 6.1**: Harmful fishing like bottom-trawling or overfishing.
In demonstration	**Solution 2.3:** Include visual cues, like paints.	See -> **Ecological impact 2.3:** Reduced survival of avian species due to collision.
	Solution 2.6: Detection based active curtailment.	
	Solution 2.7: Curtail at low wind speeds, dawn and dusk.	
	Solution 2.8: Active deterrence systems.	
	Solution 3.7: Hydro Sound Damper (HSD) methods.	See --> **Ecological impact 3.4**: Noise pollution from pile driving.
	Solution 6.2: Wildlife-safe overhead wires and poles.	See -> **Ecological impact 2.3**: Reduced survival of avian species due to collision.
	Solution 6.7: Subsidise passive fisheries methods.	See --> **Ecological impact 6.1**: Harmful fishing like bottom-trawling or overfishing.
In development	**Solution 1.6:** Incorporate a flight corridor.	See -> **Ecological impact 2.3**: Reduced survival of avian species due to collision.
	Solution 2.2: Maintain a minimum turbine air gap.	
	Solution 3.6: Construct with Blue piling.	See --> **Ecological impact 3.4**: Noise pollution from pile driving.

In discovery	**Solution 3.14:** Cut foundation above the seabed.	See --> **Ecological impact 3.10:** Decommissioning destroying novel ecosystem.
	See --> **Solution 3.9:** Use Acoustic Deterrent Devices. And see --> **Solution 3.8:** Hide sound with bubble curtain.	**Ecological impact 3.11:** Noise pollution during the disassembly.
	>>> Restores >>>	
TRL of solution	*Solution description*	*Ecological impact description*
In deployment	**Solution 5.5:** Place large artificials reefs, like SeaCult Reef System.	**Ecological impact 3.3:** Increase biomass of target species and their prey and **Ecological impact 4.1:** Hard substrate for epibenthic species to
	Solution 5.6: Place small 3D printed units, like Reef Balls®.	
In demonstration	**Solution 3.2:** Include water replenishment holes.	**Ecological impact 3.2:** Shelter for macrofauna.
	Solution 3.3: Include add-on steel gabion cages.	See --> **Ecological impact 3.3:** Increase biomass of target species and their prey.
	See --> Any restoration solution.	**Ecological impact 3.6:** Habitat loss underneath foundation.
	Solution 4.1: Add heterogeneous calcareous rocks.	See --> **Ecological impact 3.3:** Increase biomass of target species and their prey. And see --> **Ecological impact 4.1:** Hard substrate for epibenthic species to settle.
	Solution 4.2: Adapt existing armour layer.	
	Solution 4.10: Place oyster gabions.	**Ecological impact 4.6:** Habitat for juvenile fish and epibenthos. And see --> **Ecological impact 3.1**: Influx of $CaCO_3$ material into ecosystem.
	Solution 4.11: Add reef-stimulating materials.	**Ecological impact 3.1:** Influx of $CaCO_3$ material into ecosystem.
	Solution 4.12: Remote settling of spat.	**Ecological impact 4.7:** Reintroduction of reef-builders.
	Solution 5.2: Place broodstock basket, like WERC-dock.	
	Solution 5.3: Place broodstock tables.	
	Solution 6.4: Reward coexistence with organic aquaculture.	See --> **Ecological impact 6.1**: Harmful fishing like bottom-trawling or overfishing.
In development	**Solution 1.1:** International collaboration on MSP.	**Ecological impact 1.1:** Preserve marine connectivity.
	Solution 1.7: Include positive ecological impacts in EIAs.	See --> all ecological impacts with a restoration mitigation solution.
	Solution 1.8: Increase funding for nature inclusivity.	
	Solution 3.1: Co-locate with passive aquaculture.	See --> **Ecological impact 3.1:** Influx of $CaCO_3$ material into ecosystem, but one-off.
	Solution 4.3: Add mesh nets filled with quarry rock.	See --> **Ecological impact 3.3**: Increase biomass of target species and their prey. And see --> **Ecological impact 4.1:** Hard substrate for epibenthic species to settle.
	Solution 4.4: Use ECOncrete® Scour Protection Units.	**Ecological impact 4.2:** Decrease domination of invasive species. And see --> **Ecological impact 3.3**: Increase biomass of target species and their prey.
	Solution 4.5: Use anti-scour frond mattresses.	See --> **Ecological impact 3.3:** Increase biomass of target species and their prey.
	Solution 4.6: Cover cables with mat-type protection.	**Ecological impact 4.3:** Colonisation of benthic epifauna.
	Solution 5.1: Rewild life adult reef building species.	See --> **Ecological impact 4.7**: Reintroduction of reef-builders.
	Solution 5.4: Place biodegradables structures, like Treef and Geowall.	See --> **Ecological impact 3.3**: Increase biomass of target species and their prey. And see --> **Ecological impact 4.1:** Hard substrate for epibenthic species to settle.
In discovery	**Solution 3.15:** Relocate habitat upon disassembly.	See --> **Ecological impact 3.10**: Decommissioning destroying novel ecosystem.
	Solution 4.9: Add previously submerged materials.	**Ecological impact 4.5:** Lower emission from repurposed materials. And see --> **Ecological impact 3.3:** Increase biomass of target species and their prey. And see --> **Ecological impact 4.1:** Hard substrate for epibenthic species to settle.
	>>> Offsets >>>	
TRL of solution	*Solution description*	*Ecological impact description*
In demonstration	**Solution 2.4:** Build artificial nesting structures.	See --> **Ecological impact 2.3:** Reduced survival of avian species due to collision.
In development	**Solution 6.8:** Biodiversity offsetting.	See --> all ecological impacts that do not contain a mitigation solution to avoid them. These require some offsetting to achieve net zero impact.
In discovery	**Solution 2.1:** Include seal haul-out platforms.	**Ecological impact 2.2:** Habitat loss.
	To some extent unavoidable, see --> **Solution 6.8:** Biodiversity offsetting.	See --> **Ecological impact 3.5**: Sediment dispersal impairing benthic species.
	>>> Unknown >>>	
TRL of solution	*Solution description*	*Ecological impact description*

In deployment	**Solution 6.9:** Research marine ecosystems in OWFs.	See --> All ecological impacts of which the mitigation solution is unknown.
	Solution 6.10: Research enabling monitoring technologies.	
	See --> **Solution 6.9:** Research marine ecosystems in OWFs. And see --> **Solution 6.10:** Research enabling monitoring technologies.	See --> **Ecological impact 2.3:** Reduced survival of avian species due to collision.
		Ecological impact 2.1: Cumulative metocean influences.
		Ecological impact 1.2: Cumulative hydrodynamic influences.
		See --> **Ecological impact 1.7:** Introduction of nonindigenous species.
		See --> **Ecological impact 3.7:** Entanglement risk for marine megafauna.
		Ecological impact 3.8: The mooring lines scraping benthos.
		Ecological impact 3.9: Toxic effects of antifouling paints.
		Ecological impact 5.1: Desalination and cooling of offshore hydrogen.
		Ecological impact 5.2: Antifouling chemicals of offshore hydrogen.
		Ecological impact 5.3: Increased salinity of offshore hydrogen.
		Ecological impact 5.4: Noise pollution offshore hydrogen.
		Ecological impact 5.5: Warmed seawater of offshore hydrogen.
		Ecological impact 5.6: Deficit of light large scale floating pv.

What cannot be overlooked are the ecological impacts of which their mitigation solution is still unknown. For this, the TRL of solutions is irrelevant because each of these ecological impacts can only begin to be addressed by further research. This research can be both into marine ecosystems in OWF (Solution 6.9) and the development of enabling monitoring technologies (Solution 6.10). These two research areas are *in deployment,* and arguably are best utilised by focussing on ecological phenomena of which their mitigation hierarchy status is unknown. Focus areas here are cumulative hydrodynamic and hydrodynamic impacts of OWFs (Vrooman et al., 2019); Ecological impacts offshore hydrogen production which is commonly planned in co-location with future OWFs; and the Biochemical effects of toxic antifouling chemicals used on cable paints and in hydrogen wastewater (Witteveen+Bos, 2024). These topics may be considered the blind spot of nature inclusivity in OWFs, as their resolutions are not even *in discovery* yet.

4.3 Insights from interviews

The next section summarises the key information uncovered during the interviews with experts working on nature inclusivity across the OWF sector. Appendix 1 contains the full interview notes. Table 6 summarises the main takeaways and overarching themes that were touched upon throughout the interviews. Specifically, this table displays how many times a certain opinion, view or sentiment was shared, and by who.

Table 6. Overarching themes and main takeaways from the seven interviews, where an X indicates an opinion with the sentiment of a given takeaway was opted by this particular interviewee.

	Interviewee #1 (Offshore marine contractor)	**Interviewee #2** (OWF operator)	**Interviewee #3** (OWF developer and operator)	**Interviewee #4** (NGO)	**Interviewee #5** (OWF developer and operator)	**Interviewee #6** (Grid operator)	**Interviewee #7** (Research institute)
7 out of 7 interviewees: Were sceptical of usefulness of deploying playground-type small scale artificial reefs.	X	X	X	X	X	X	X
6 out of 7 interviewees: Said it is preferrable to first try to avoid and minimise ecological impacts, before commencing in restoration efforts. Particularly bottom trawling should be avoided and minimised to enhance a novel OWF ecosystem.		X	X	X	X	X	X
5 out of 7 interviewees: Thought collaboration with NGOs and academia should be further stimulated.		X	X	X	X		X
5 out of 7 interviewees: Considered active reintroduction of marine life as an important solution in nature inclusivity in OWFs.	X	X	X		X	X	
5 out of 7 interviewees: Believed marine conservation and restoration efforts must match the needs and state of the local area.	X		X		X	X	X
4 out of 7 interviewees: Argued that scalability and the ability to integrate into the base case park design, are the most important traits of a nature inclusive solution.	X		X		X	X	
4 out of 7 interviewees: Argued that natural, recycled and locally sourced materials are preferred over processed shipped materials.	X				X	X	X
4 out of 7 interviewees: Thought that policy makers should focus tender criteria on ecosystem outcomes and ecological threshold, but leave it to the OWF developer to determine how to meet these.			X	X	X		X
3 out of 7 interviewees: Believed that there is a need for national and international marine spatial planning with regards to nature in OWFs.	X		X	X			
3 out of 7 interviewees: Argued that understudied ecological impacts of OWFs are the ones that are harder to understand or are less marketable.			X	X		X	
2 out of 7 interviewees: Thought that OWF disassembly requirements are currently incomplete or not in favor of nature.	X				X	X	
2 out of 7 interviewees: Pointed out nature inclusivity solutions for floating turbines should focus more on the pelagic than the benthic, due to their depth.	X						X
2 out of 7 interviewees: Believed cumulative hydrographic impacts are understudied.			X	X			
2 out of 7 interviewees: Mentioned offshore hydrogen as a potential big new ecological thread.				X		X	
2 out of 7 interviewees: Argued for invasive species to not necessarily be an ecological risk of OWFs in the North Sea, as long as they contribute to a balanced system.			X	X			

Among all seven interviewees there was a sense of scepticisms towards artificial reef startups selling ‘cool’, ‘funky’ and ‘artsy’ sculptures. Some stated that OWFs should not be designed as playgrounds, or that fish don’t care what their habitat looks like. Ffour interviewees argued that for there to be a positive impact on a population scale, artificial reefs are too small. Instead, these four interviewees reasoned that marine ecosystems are best supported through solutions that can be implemented at the largest possible scale. By integrating habitat restoration into the base case design and landscaping of an OWF, such scalability can be achieved (Ter Hofstede et al., 2023). Adapting existing scour protection to include calcareous rock material of varying sizes is preferred over sophisticated artificial reef units, as they provide similar structural complexity but at a lower cost (Ter Hofstede et al., 2023). As one interviewee stated, '*Scalability of solutions is preferred over singular fish hotels, cubes, balls, lobster cages, etc. as these don't have any influence at a population level'.* Five interviewees considered active reintroduction of marine life as an important solution in nature inclusivity in OWFs. Each of them voiced that remote settling of larvae on scour protection is the most promising method to achieve this for the European flat oyster in the Dutch North Sea. Remote settling, or outplacing, is a novel technique, where oyster larvae are grown on rocks in a laboratory environment (Tonk et al., 2020). Rock material used for cable and scour protection is then loaded with spat, and during construction integrates with the build (Tonk et al., 2020). By integrating the reintroduction of reef-builders into the base case design of an OWF, this solution becomes more scalable, compared to the more costly installation of standalone oyster beds (Ter Hofstede et al., 2023). On four occasions, the sentiment submerged that 3D designed and printed artificial reef units are less preferable from a sustainability perspective. Natural and locally sourced materials have a lowed carbon footprint than shipped and finely crafted concrete. This often contains toxins (Ter Hofstede et al., 2023). One interviewee stated, '*It makes no sense to extensively process rock material when you can just get it from the quarry directly, as long as it is rich in calcium carbonate*.'

A number of issues were brought up separately by two interviewees: The policy around OWF disassembly insufficiently serving the ecosystem created at the end-of-life of an OWF; Nature enhancements in floating turbines needing to focus on the pelagic instead of the benthic zone; Water temperature changes and antifouling chemicals of offshore hydrogen systems posing a new ecological thread; Introduction of exotic marine species not being a major thread in a marine system like the North Sea; Cumulative hydrographic impacts, such as changes in stratification, being understudied. Like the ecological impacts of offshore hydrogen, understudied topics were thought to be the ones that are harder to understand or are less marketable, according to three interviewees. With one stating that '*Policy makers unfortunately focus mostly on the big 'huggable' species, like marine mammals. However, smaller less visible species at the lower trophic levels are just as important to protect and conserve. Or tube worms for example are good reef builders and phytoplankton for primary productivity*.' Another stated that this is the reason why reef restoration receives more attention than pressing issues. These include noise pollution, cable paint toxicity and the disturbance electromagnetic fields of cables to marine fauna's ability to navigate. '*Too complicated to pitch and win extra funding for*'.

Another reoccurring view emerging across several interviews, was that not all responsibility of nature enhancement can be attributed to OWF developers on their own. Five interviewees believed it best that collaboration with NGOs and academia should be further stimulated. Further monitoring and research should be undertaken to better understand ecosystem functioning in OWFs. Three interviewees saw a need for improved national and international marine spatial planning with regards to nature in offshore wind. It was mentioned that small scattered ecological enhancement projects have less impact on the ecosystem. One interviewee stated *'Target areas should be created for specific nature goals. We should not want to do a bit of everything everywhere, because when for example oyster restoration efforts are too fragmented, they don't work. And if they are done in the wrong place, it doesn't work either.*' Five interviewees argued in favor of rea-wide planning, not park-specific planning of nature inclusivity in OWFs. Simultaneously, five interviewees also stated that restoration projects must match the local area and there is not a one size fits all solution. One interviewee explained that by mapping stressor/receptor interactions (i.e. the ecological impacts and the impacted species) in a particular area, the most suitable nature protection and enhancement can be implemented. For example, oyster restoration is best located in areas that historically contained oyster beds (Sas et al., 2023).

Related to this, four interviewees thought that policy makers should design tender criteria to include ecological thresholds and ecosystem outcome requirements and give OWF developers liberty in how to abide to these. One interviewee offered that instead of doing an *environment impact assessment*, conduct an *environmental outcome assessment*: Instead of assessing how to mitigate the impacts of activities, envisioning how to design a healthy ecosystem. This statement reflects the separation of nature protection and nature enhancement within OWF development. Nature protection is a consenting requirement and relates to avoiding and minimising negative ecological impacts. Nature protection on the other hand is seen as bonus points on tender bits, scored by the corporate sustainability department. As the mitigation hierarchy theory states, the two are not separated topics but should be addressed in synergy. Six interviewees agreed that avoiding and minimising impacts is still more important than restoration efforts, particularly with regards to seafloor disturbing activities like bottom-trawling. It was mentioned that trawl net fishing is not common near OWFs for logistical reasons. However, it is not by default prohibited and therefore a mitigation solution that should not be for granted. One interviewee stated, *'Don't try to enhance anything that you aren't protecting.'* This insinuates there is a responsibility for the government and fisheries sector to assure the health of the novel ecosystems growing at the base of turbines.

4.4 Q2: Species abundance and composition in OWF Hollandse Kust Zuid

The ROV footage captured in HKZ provides an initial insight into the benthic and pelagic species present in this North Sea OWF with its artificial reefs as a means of nature enhancement. The next section will describe the species encountered across varying substrates (reef, scour protection, cable and sand) and the ecological trends herein, in as far as this proof-of-principle study can deliver such knowledge.

Firstly, the species richness across the four surveyed substrates is as follows: On scour protection fifteen unique species were observed. On reef substrate this number was fourteen and the species richness of cable and sand substrates were ten and eleven, respectively. This includes the different types of species encountered across both counting methodologies, though it should be noted that this leaves the overall species richness per substrate incomplete. Various species, such as *Hydrozoans* and *Sabellaria*, were excluded from both counting methods. They were either too abundant to register or too complex to distinguish between individuals within the footage.

Table 7 shows species abundance per turbine location and substrate expressed per 100 m2 as derived from the CVAT annotation counting method. Notably the substrates, due to the flight path of the ROV, were not surveyed in equal quantities, but standardised to 100m2. The Kruskal-Wallis rank sum test indicated there is no significant difference in the composition of species across the different substrate totals: chi-squared = 0.14511, df = 3, p-value = 0.9859. The p-value indicates a very high probability that the observed differences in medians are due to chance.

Table 7. Species counts per 100 m^2 of substrate, as derived from CVAT annotation counting method.

		Reef			Scour protection					Cable			Sand				
		A3	B2	Total	A3	B2	D1	D2	Total	D1	D2	Total	A3	B2	D2	Total	
Common name	**Name**	80.56	71.42	151.98	27.03	20.76	91.77	129.04	268.6	7.33	7.84	15.17	52.18	11.87	9.66	73.71	m2 surveyed
Brown crab	Cancer pagurus	22.3	25.2	23.7	37.0	48.2	113.3	89.9	89.4	27.3	102.0	65.9	15.3	0.0	0.0	10.9	
Velvet swimming crab	Necora puber	34.8	36.4	35.5	22.2	0.0	148.2	108.5	105.0	81.9	76.5	79.1	11.5	0.0	20.7	10.9	
Hermit crab	Pagurus bernhardus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Unidenfitied crab	Decopoda unidentified	17.4	240.8	122.4	81.4	19.3	69.7	71.3	67.8	27.3	51.0	39.6	19.2	16.8	0.0	16.3	
Total crabs	**Total decopoda**	**74.5**	**302.4**	**181.6**	**140.6**	**67.4**	**331.3**	**269.7**	**262.1**	**136.4**	**229.6**	**184.6**	**46.0**	**16.8**	**20.7**	**38.0**	
Common starfish	Asterias rubens	1633.6	1128.5	1396.2	6629.7	3699.4	43.6	37.2	985.9	27.3	76.5	52.7	191.6	67.4	0.0	146.5	
Serpent star	Ophiura ophiura	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	88.2	50.5	0.0	70.5	
Common brittle star	Ophiotrix fragilis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Unidentied starfish	Echinoderm unidentified	34.8	0.0	18.4	37.0	0.0	0.0	0.0	3.7	0.0	0.0	0.0	61.3	0.0	0.0	43.4	
Total starfishes	**Total echinoderm**	**1668.3**	**1128.5**	**1414.7**	**6666.7**	**3699.4**	**43.6**	**37.2**	**989.6**	**27.3**	**76.5**	**52.7**	**341.1**	**117.9**	**0.0**	**260.5**	
Blue mussel	Mytilus edulis	5.0	0.0	2.6	125.8	0.0	2456.1	1044.6	1353.7	81.9	1096.9	606.5	210.8	0.0	0.0	149.2	
Common Atlantic slippersnail	Crepidula fornicata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2673.9	3290.8	2992.7	0.0	0.0	0.0	0.0	
Total shellfishes	**Total mollusca**	**5.0**	**0.0**	**2.6**	**125.8**	**0.0**	**2456.1**	**1044.6**	**1353.7**	**2755.8**	**4387.8**	**3599.2**	**210.8**	**0.0**	**0.0**	**149.2**	
Common dragonet	Callionymus lyra	0.0	2.8	1.3	0.0	0.0	6.5	1.5	3.0	27.3	0.0	13.2	3.8	0.0	0.0	2.7	
Whiting pout	Trisopterus luscus	1003.0	2240.3	1584.4	1605.6	4171.5	4.4	1125.2	1026.1	0.0	790.8	408.7	528.9	22510.5	0.0	3999.5	
Striped red mullet	Mullus surmuletus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	16.8	0.0	5.4	
Rock gunnel	Pholis gunnellus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Atlantic cod	Gadus morhua	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Unidenftified fish	Pisces unidentified	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Total fishes	**Total pisces**	**1003.0**	**2243.1**	**1585.7**	**1605.6**	**4171.5**	**10.9**	**1126.8**	**1029.0**	**27.3**	**790.8**	**421.9**	**536.6**	**22527.4**	**0.0**	**4007.6**	
Mud sagartia	Cylista troglodytes	312.8	190.4	255.3	125.8	86.7	161.3	91.4	118.4	27.3	76.5	52.7	479.1	0.0	0.0	339.2	
Plumose anemone	Metridium senile	1037.7	576.9	821.2	776.9	452.8	3266.9	5243.3	3748.3	1118.7	8061.2	4706.7	49.8	0.0	124.2	51.6	
Sandalled anemone	Actinothoe sphyrodeta	196.1	425.7	304.0	96.2	0.0	43.6	57.3	52.1	0.0	204.1	105.5	0.0	0.0	0.0	0.0	
Unidentified anemone	Anthozoa unidentified	1827.2	719.7	1306.8	1916.4	973.0	1451.5	708.3	1104.2	327.4	841.8	593.3	1234.2	5661.3	41.4	1790.8	
Total anemones	**Total anthozoa**	**3373.9**	**1912.6**	**2687.2**	**2915.3**	**1512.5**	**4923.2**	**6100.4**	**5023.1**	**1473.4**	**9183.7**	**5458.1**	**1763.1**	**5661.3**	**165.6**	**2181.5**	

Dunn's test results, in table 8 confirm that there are no significant differences in composition between any pairs of substrates. This suggests that the composition distributions are quite similar across the substrates for the species tested. For individual species, there is no evidence of significant differences in abundance among the substrates, as the p-values of Dunn's test performed on a species level were all higher than 0.05 (see appendix 3). This further supports the conclusion that the type of substrate does not significantly affect species abundance in your dataset.

Table 8. Dunn (1964) Kruskal-Wallis multiple comparison p-values adjusted with the Bonferroni method of species composition across varying OWF substrates, as derived from the CVAT annotation counting method.

Comparison	Z	P.unadj	P.adj
Cable - Reef	0.23837621	0.8115893	1
Cable - Sand	0.29446473	0.7684028	1
Reef - Sand	0.05608852	0.9552713	1
Cable - Scour	0.00000000	1.0000000	1
Reef - Scour	-0.23837621	0.8115893	1
Sand - Scour	-0.29446473	0.7684028	1

Nevertheless, it can be of interest to analyse observations that are not statistically significant and visualise the counts per 100m2 of substrate per species as derived from the CVAT annotation counting method (see figure 7). Here it can be seen, for in stance, that *Crepidula fornicata* only prevails on cable substrate, *Ophiura ophiura* and *Mullus surmuletus* only on sand. *Trisopterus luscus* was observed in the highest abundances on sand substrate, followed by reef, then scour protection and the lowest abundances on cable. *Callionymus lyra* appears most observed on cable, then scour protection and sand and least on reef substrate. Importantly none of these trends are statistically significant and thus should all be interpreted with caution.

Whilst it remains impossible to draw clear conclusions on the variance across substrates, some species appear to be most abundant within their respective group (see table 7 and figure 7). *Asterias rubens* is the *Echinoderm* that is most abundantly present. For the *Pisces* this is the *Trisopterus luscus* and for the *Anthozoa* it is *Metridium senile*. This hints at a favorable relationship between each of these three species and the novel marine ecosystem that an OWF fulfils. Either this ecosystem is particularly suitable for these three species or they can adapt particularly well to it, compared to their family relatives.

Figure 7. Bar graph visualisation of counts per 100 m² of substrate per species, as derived from CVAT counting method.

Table 9 shows a breakdown of species abundance by both turbine location and substrate expressed as a number per 100 m2 as derived from the video tallying counting method. As can be seen, a few fish species are recorded in these results that did not come up in the CVAT annotation counting method. The Kruskal-Wallis rank sum test on the video tallying counting method indicated there is again no significant difference in species composition among the substrates totals: chi-squared = 5.2153, df = 3, p-value = 0.1567. The p-value indicates that the differences in medians could likely arise from random variation.

Table 9. Species counts per 100 m^2 of substrate, as derived from the video tallying counting method.

		Reef			Scour protection					Cable			Sand				
		A3	B2	Total	A3	B2	D1	D2	Total	D1	D2	Total	A3	B2	D2	Total	
Common name	**Name**	80.56	71.42	151.98	27.03	20.76	91.77	129.04	268.6	7.33	7.84	15.17	52.18	11.87	9.66	73.71	m2 surveyed
Common dragonet	Callionymus lyra	2.5	0.0	1.3	0.0	0.0	18.5	0.0	6.3	13.6	0.0	6.6	13.4	0.0	0.0	9.5	
Striped red mullet	Mullus surmuletus	1.2	2.8	2.0	3.7	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	59.0	0.0	9.5	
Rock gunnel	Pholis gunnellus	1.2	0.0	0.7	0.0	0.0	7.6	0.0	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Atlantic cod	Gadus morhua	7.4	4.2	5.9	11.1	0.0	1.1	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
European plaice	Pleuronectiformes platessa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.7	0.0	0.0	4.1	
Tompot blenny	Parablennius gattorugine	3.7	0.0	2.0	0.0	0.0	1.1	2.3	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Poor cod	Trisopterus minutus	1.2	2.8	2.0	0.0	0.0	1.1	1.5	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Shorthorn sculpin	Myoxocephalus scorpius	0.0	0.0	0.0	0.0	0.0	2.2	0.8	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Table 10 summarises the Dunn's test results of differences in composition between any pairs of substrates for this counting method. The results here further support the lack of significant differences in abundance among substrates. Cable - Scour has a p-value of 0.03986216, which is below the conventional threshold of 0.05. This indicates potential significance for that specific comparison. However, given the context and the overall results, it may not indicate a robust difference, especially with the Bonferroni adjustment applied. While one comparison showed potential significance, it does not indicate a robust difference due to the overall results.

Table 10. Dunn (1964) Kruskal-Wallis multiple comparison p-values adjusted with the Bonferroni method of species composition across varying OWF substrates, as derived from the video tallying counting method.

Comparison	Z	P.unadj	P.adj
Cable - Reef	-1.8862560	0.05926046	0.3555628
Cable - Sand	-1.2387353	0.21544354	1.0000000
Reef - Sand	0.6475207	0.51729499	1.0000000
Cable - Scour	-2.0551745	0.03986216	0.2391729
Reef - Scour	-0.1689184	0.86586079	1.0000000
Sand - Scour	-0.8164392	0.41424900	1.0000000

For individual species in the video tallying counting method, there also is no statistically significant difference in abundance across substrates. As here too, the p-values of Dunn's test performed on a species level were all higher than 0.05 (see appendix 3). The counts per 100m2 of substrate per species, as derived from the video tallying counting method, reveal a number of patterns, though not statistically significant (see figure 8). Most importantly, *Pholis gunnellus* and *Gadus morhua* have been sighted after all. They were so scarce that the CVAT annotation counting methods overlooked them entirely. Four more species prevailed that were overlooked in the CVAT annotation counts, including *Pleuronectiformes platessa*, *Parablennius gattorugine*, *Trisopterus minutus* and *Myoxocephalus scorpius*. Of these relatively rare fish species. Leaving the schools of *Trisopterus luscus* out of consideration, it can be noted that *Callionymus lyra* and *Mullus surmuletus* are relatively more abundant than all other *Pisces*. Both appear most abundant on sand over any other substrate, although this is not a statistically significant trends as well all substrate comparisons (see figure 8). *Pleuronectiformes platessa* was only sighted on sand and similarly *Myoxocephalus scorpius* only on scour protection. Although the latter was only sighted once and therefor this can be coincidence. *Pholis gunnellus* appears more abundant on scour protection than on reef substrate, yet is absent from sand and cable substrate entirely. The reverse pattern is true for *Gadus morhua*, *Parablennius gattorugine* and *Trisopterus minutus*. These species appear to be more abundant on reef than on scour and weren't encoutered on sand and cable at all. For *Gadus morhua* the difference in abundance between reef and scour protection substrate is the largest. This hints at the suitability of the reef for this umbrella species. Importantly, these findings were not statistically significant.

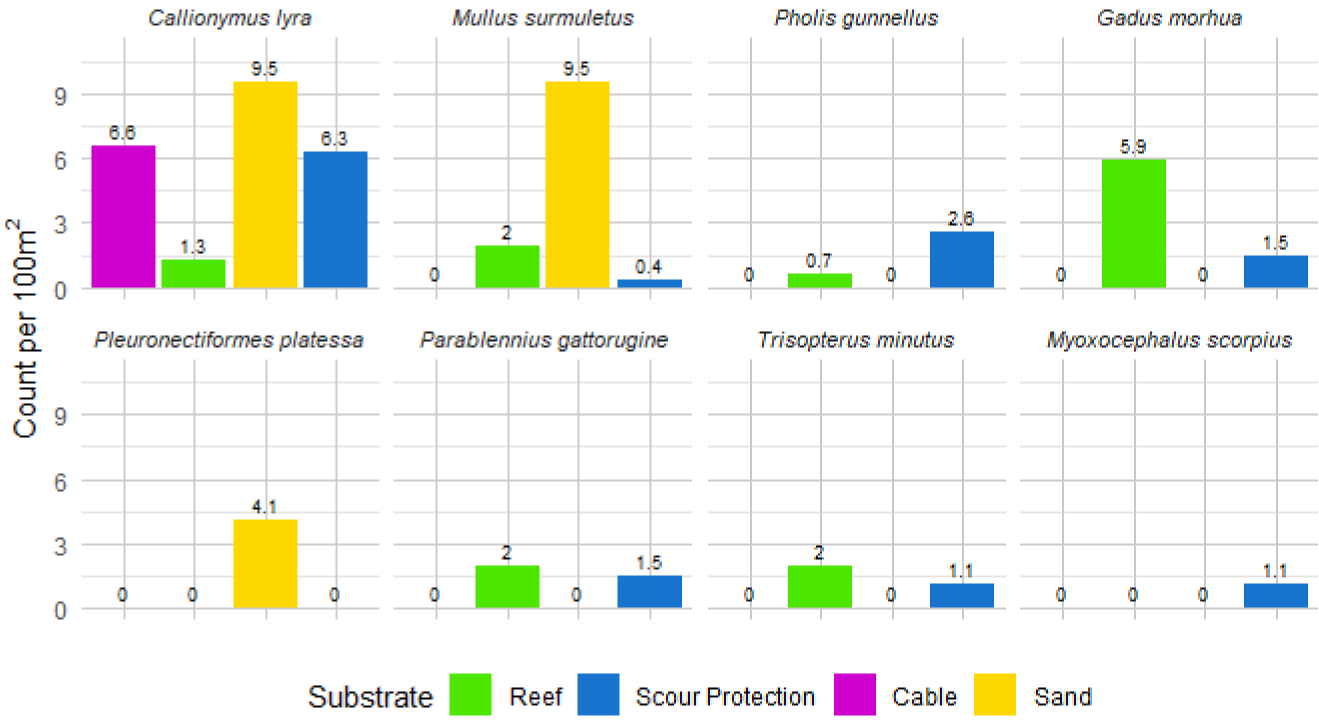


Figure 8. Bar graph visualisation of counts per 100 m² of substrate per species, as derived from the video counting method.

Lastly, as this is a proof-of-principle study, it is worth comparing the overall species counts across the two different counting methods: CVAT annotation and video tallying. Four fish species were counted in both methods and reveal the discrepancy the de results attained in the two different counting methods (see figure 9). As stated earlier, *Pholis gunnellus* and *Gadus morhua* were invisible in the CVAT annotation counting method. Without the video tallying it would have been impossible to establish the preliminary trend of *Gadus morhua* potentially being more abundantly represented at the reef substrate than at the scour protection. In the CVAT annotations, *Mullus surmuletus* did appear on sand substrate but tallying it from the video footage revealed that it was underrepresented as the abundance on sand was higher. It also appeared on reef and scour substrate which the CVAT annotations missed. *Callionymus lyra* illuminates the discrepancy between both counting methods. This species was more abundant in the CVAT annotation counts then in the video tallying on the cable substrate. However on the sand and scour protection substrate *Callionymus lyra* was more abundant in the video tallying than in the CVAT annotations counts. This again hints at both the CVAT annotation counting overlooking uncommon species. The counts per substrate being appear to be influenced by the counting method. As described the CVAT annotation counting method contains an oversimplification of counts per substrate. Every frame was given a single substrate whilst commonly the substrate visible within a frame was a combination of substrates.

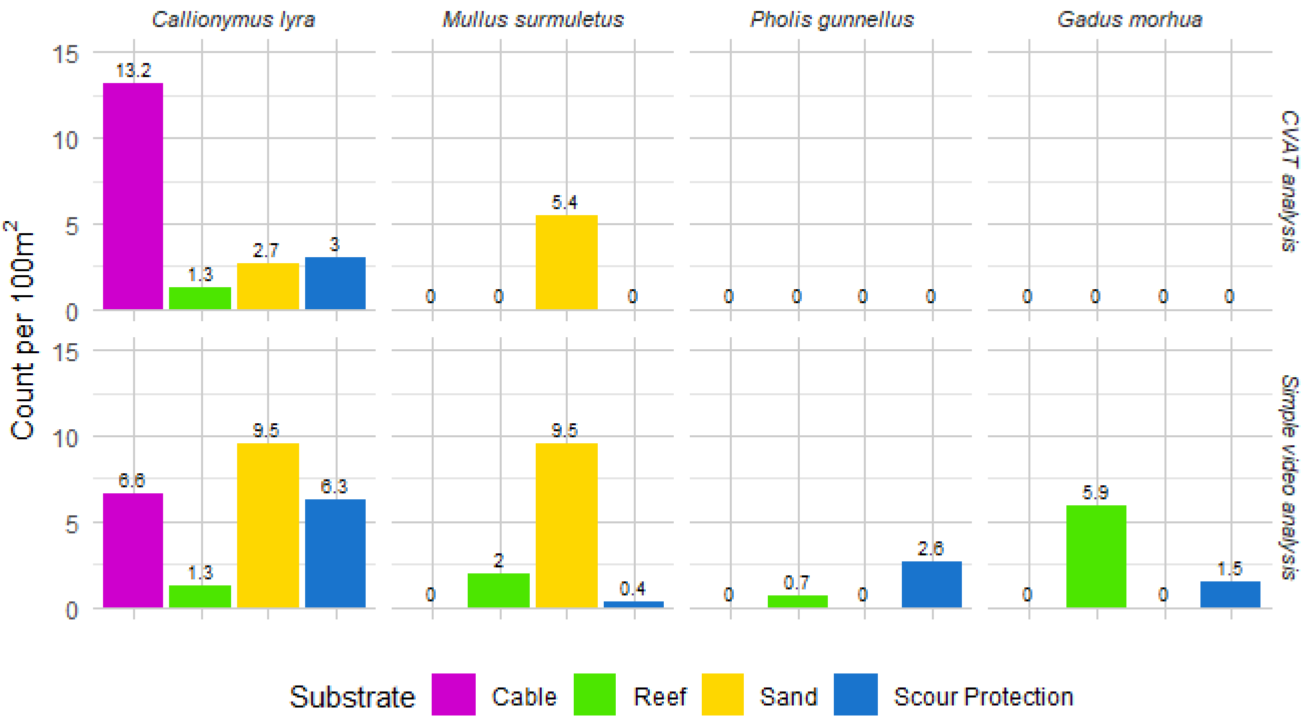


Figure 9. Derived counts per 100 m² of substrate per species resulting from the CVAT annotation analysis as compared to video tallying analysis.

5. Discussion

The next chapter seeks to place the findings of this study into the greater context of existing scientific knowledge on the developments of OWFs and the ecological implications thereof. First, the ecological implications of the large-scale expansion of OWFs and their long-term deployment in the marine space will be discussed. The ecological risks and uncertainties of OWFs will be further illuminated, to discuss how nature inclusive solutions are to these into account. Next, future trends in offshore renewable energy infrastructure are discussed. This includes the rise of floating turbine technology, the growing competition over ocean space and the resulting need for co-location. Here, attention will be brought to the adaptations required of nature inclusivity in OWFs, due to co-locating with aquaculture, floating solar and offshore hydrogen. Lastly, considering the results of the HZK case study, implications for the improvement of marine research in OWFs at large are addressed.

5.1 Ecological risks and uncertainties of OWFs

Throughout two expert interviews the view arose that in the North Sea, invasive marine species are not unwelcome by fault. The sentiment being, if they do not cause an imbalance in predator-prey dynamics, there is no need to try to prevent such species from inevitably immigrating. Arguably this view can hold value for a degraded ecosystem like the North Sea, which has undergone centuries of anthropogenic influence. Though, in areas with persisting ecological value, this line of reasoning should be taken with great caution. The introduction of nonindigenous species is a serious risk of both OWF development and nature enhancement therein (Hermans et al., 2024). Artificial structures in the marine environment are known entry points for settlement of invasive epibiota (Glasby et al., 2007). Biofouling, the accumulation of micro-organisms, plants, algae, or animals to surfaces (Van Pelt et al., 2015), on OWF infrastructure is currently the least regulated treat of non-indigenous species invasions worldwide. Blocking of habitat by non-target species is considered one of the highest risks of nature inclusive solutions (Hermans et al., 2020).

The cumulative hydrodynamic and metocean impacts of OWFs arose as a majorly understudied aspect of nature inclusivity in OWFs. The small-scale artificial reef effect at turbine level, is reasonably understood to be positive to the local ecosystem (Degraer et al., 2020). Unlike the large-scale effects, arising from the countless OWF developments underway across ocean space globally. They hint at increased connectivity of benthic fauna by larval transport, although such a stepping stone effect is yet to be studied (Degraer et al., 2020). Knowledge gaps in ecological impacts of OWFs crystallise immediately when scoping up to the large-scale expansion of OWFs, their long-term influence and when combining their impacts with those of other maritime sectors. A major task herein is identifying ecological thresholds and when these are exceeded (Leander Vølstad et al. 2022). Some negative impacts of OWF construction, such as collision with and noise disturbance to sea life, are mitigatable on their own. Other risks, for instance those associated with electromagnetic fields and chemical pollutions aren't as well understood yet. It is the cumulative impact of these known and unknown ecological impacts, that poses the biggest risk to nature, according to North Sea Foundation (2022).

Understanding both the trophic cascades and the ecosystem-level effects of OWFs requires timely life-cycle-assessments (LCA) with field monitoring and quantitative model simulation (Wang et al., 2024). Li et al. (2023) was the first to conduct an LCA on OWFs in the North Sea. They concluded no net adverse impacts on the benthic communities inhabiting the originally sandy bottom, whilst the generated artificial reefs having the potential to double species richness and increase species abundance by a two-order-of-magnitude. As of yet, there is a high degree of agreement on type (positive or negative) of impacts to ecosystem structure, function and processes. However, the certainty regarding the magnitude of OWF's ecological impacts is low, because empirical evidence is still scarce (Galparsoro et al., 2022).

5.2 Future trends in offshore renewable energy infrastructure

Whilst floating turbines are not yet commercially viable for large-scale deployment, their market share is expected to grow, due to their deployability in deeper waters (DNV, 2021). DNV (2021) forecasts that within this decade significant technological developments will reduce costs to improve its scalability. Floating wind turbine technology can be seen as a prominent upcoming development to the infrastructure and locations of future OWFs. However, this study brings to light new challenges and opportunities to nature protection and enhancement. The framework includes entanglement of the mooring lines as well as noise pollution of the mooring lines as potential new disruptions to marine fauna. Nevertheless, the installation of floating turbines requires no pile driving, thereby avoiding the source of louder acoustic pollution in the first place. Another ecological impact, specific to the build of floating turbines, was identified to be that of their mooring lines scraping over the seabed. Arguably, this means that scour enhancements around anchor points are unsuitable as nature inclusivity solutions for floating turbines. Additionally, micrositing an OWF with predominantly floating turbines required additional sophistication to avoid the mooring lines scraping over ecologically valuable habitat. This would practically equate to the bottom disturbance of trawl nets. Any standalone structures to stimulate settlement or function as habitat should be placed outside of the vicinity of the mooring lines. Though expert interviewees agreed that add-on elements are less preferable compared to nature inclusivity adaptations that can be made to the base case design of OWFs. Floating turbines are suitable only for deeper waters and habitat restoration structures may not combine well with the seafloor scraping mooring lines. Therefore it can be advised that floating OWFs focus nature inclusivity efforts on the pelagic instead of the benthic region. For example, by nurturing the fish population by culturing mussels or seaweeds in between turbines. Alternatively, floating OWFs can focus above water, on bird migration modelling, detection curtailment systems and artificial nesting structures, should they strive to deliver a net positive ecological impact.

DNV (2022) forecasts that by 2050, OWFs will require 82% of the total area of ocean space globally. This extensive spatial claim over ocean space (Hermans et al., 2020) places the OWF industry in direct competition with other maritime uses: Shipping, fisheries, aquaculture, military, tourism, nature and resource extraction including oil, gas, sand and precious metals (Steins et al., 2021). Deep-sea mining of marine minerals such as Mn nodules, FeMn crusts and seafloor massivesulfide deposits, whilst controversial for its understudied ecological impacts, is driven by the energy transition (Koschinsky et al. 2018). With electrification and battery technologies being impossible to build without cobalt, copper, lithium and nickel and onshore mines predominantly located under unstable regimes, the unclaimed ocean is a welcome source for Western mining companies to exploit (DNV, 2022), despite this contributing to geopolitical unrest at sea.

The increasing competition of ocean space provides ample opportunity for multi-functional use of space (Van den Boogaart et al., 2020). Though if not carefully managed may only trigger a race for space and conflict with other maritime stakeholders (Pettersen et al., 2023). Four types of dual use cases for OWFs can be identified. Firstly, *multi-purpose* OWFs share core infrastructure and services, for example with finfish cage aquaculture (Abhinav et al., 2020). Secondly, *symbiotic* use OWFs share peripheral infrastructure and services. For example, shared logistical systems or service vessels with aquacultural parties in the same area (DNV, 2023b) or OWFs as charging stations for electric ships (The Maritime Executive, 2023). Thirdly, *co-location* of OWFs refers to dual use of area over the same time period, without shared infrastructure. For example adopting passive fishing fear to reduce gear entanglement in (DNV, 2017). Lastly, *repurposing* refers to multi-usage of an area in subsequent order, like offshore structures decommissioned to become artificial reefs (Ramm et al., 2021).

It appears that co-location with aquaculture offers both opportunities and threats to marine ecosystems. An influx of $CaCO_3$ into the system theoretically stimulates skeleton growth (The Nature Conservancy & INSPIRE Environmental, 2021). Therefore, combining OWFs with aquaculture of extractive species, like hanging mussel cultures, could benefit natural reef builders (Ter Hofstede et al., 2023). Many more co-located aquaculture/wind technologies are trialled, such as vertical-axis wind turbines (VAWT) with fish-farming cages below and solar arrays atop a floatable (Zheng et al., 2020). Test sites in Spain and China comprise aquaculture cages attached to the base of floating and fixed-bottom turbines respectively (Mazza and Xylia, 2023). Importantly, aquaculture involving fed species is not necessarily beneficial to a marine ecosystem. Potentially under strict management, to assure a wild-captured forage fish population is sustainably harvested without surpassing the limit of its ecological supply (Froehlich et al., 2018). When asked for novel ideas for nature inclusivity in OWFs, one interviewee proposed to attach lobster cages to anchor lines. It is unclear how this benefits the population of these species, their prey or the wider food web at all. This illustrates a phenomenon that seems to have infiltrated in other departments of ecology in OWFs too: Over-innovating to the extent of inventing counterproductive novelties. Another example of this was found in Stephenson (2022), who proposes to build seal-haul out platforms at water's edge of a turbine tower. This should offer seals a place to rest, but it is unclear what benefits this has over a natural sand bank or where seals should haul-out at the end of an OWFs lifecycle, should it not be repowered.

The OWF sector is also warming up to sharing locations with other renewable technologies, like floating solar, wave energy, desalination, electrofuel and hydrogen production (Mazza and Xylia, 2023). The latter accounts for the largest number of conceptual and piloting co-located projects as of yet. This is because OWF energy generation present the lowest levelised costs at larger deployment scales for hydrogen production (Mazza and Xylia, 2023). Excess wind energy, common in the winter months, is ideal for green hydrogen generation (Jay and Toonen, 2015). With new pipelines or repurposed gas pipelines, it can be transported to fuel offtakers either ashore or on site. This study is the first to include the ecological impacts of offshore hydrogen into the realm of nature inclusivity in OWFs. The prospects of these two energy technologies being developed in conjunction with one another are substantial. Therefore, a major blind spot to nature inclusivity in OWFs, are the poorly studied changes to the chemistry and temperature of seawater when used for hydrogen production and its cooling system. Primarily, research should focus to better understanding the extent of these impacts to marine ecosystems. Secondarily, biodegradable alternatives could be tested to replace those antifouling chemicals that are found to cause proportionately the greatest toxic pollution across all trophic levels. To mitigate ecological impacts caused by unavoidable seawater temperature and salinity increases, offshore hydrogen plants may be best situated within an OWF in such a manner that the hydrodynamic conditions of the site carry processed cooling water away from any nature restoration efforts on OWF infrastructure. This too should be further researched.

Floating photovoltaics are increasingly deployed at sea, with fouling communities under observation already (Mavraki et al., 2023). Moreso, Offshore Energy Hubs (OEHs) are thought to become key features of the global energy system. OEHs can be understood as a fully renewable energy resource-based combination of assets that link at least two services, such as electricity generation, interconnection and offshore storage (Lüth and Keles, 2024). For example, a transnational underwater electricity grid (Saborit et al., 2023) connecting to multiple, instead of a single landing point, to redistribute and thereby optimise energy offtake. This overall trend towards complex energy solutions, OEHs, co-located and combined-tech, forecasts a growth in the overall quantity of offshore infrastructure. From networks of electricity cables, pipelines and service supply lines to denser assemblages of platforms, artificial islands, connectors as well as increased vessel traffic (Bueger and Edmunds, 2024). Theoretically any bottom-fixed offshore infrastructure lends itself to ecologically enhanced scour protection. As long as the rock material used is calcareous, locally sourced and heterogenous in size (Ter Hofstede, 2023). As with OWFs, OEHs would still require considerable mitigative action to avoid and minimise construction-related noise pollution and vessel-related fuel waste.

Maritime security and energy security are indeed becoming closely intertwined (Bueger and Edmunds, 2024). Since the sabotage of the Nord Stream undersea gas pipeline in the EEZ of Denmark and Sweden in 2022, there is a concerning realisation that remote offshore infrastructure could be a prime target for a maliciously attack, as a means of terrorism, grey zone warfare or even interstate conflict (Bueger and Liebetrau, 2023). Russia's systematic maritime mapping of critical infrastructure in the Baltic and North Sea have amplified the European fear for offshore sabotage (Schaller, 2024). In the winter of 2024-2025, suspected Russian sabotage incidents have occurred with an optic fibre data cable as well as power cable Estilink-2 in the Baltic Sea (BBC News, 2025). In the Indian Ocean Region the commonality of maritime terrorism is even seen as one of the main causes for India's reluctance to commence in OWF development at all (Aswani et al., 2021). Considerable damage and disruption result from an attack, whether it be with explosives, a hijacked vessel or cyber malware, particularly for those countries that are transitioning their energy reliance to offshore wind (Bueger and Edmunds, 2024). Clearly, the increased risk of maritime aggression and military presence will pose a major influence on operational OWFs and planned developments too. Destruction of offshore oil and gas infrastructure presumably unleashes a natural disaster with effects on protected and restored habitat in OWFs. The prospected increase of maritime traffic, from combined military, shipping and renewables presence, are accompanied with further vessel waste and fuel pollution (Mangesh et al., 2024).

5.3 Implications of case study for the improvement of marine research in OWFs at large

The case study of OWF Hollandse Kust Zuid provided a valuable initial insight into the benthic and pelagic species present in this section of novel North Sea ecosystem. More importantly however, this study functioned as a proof-of-principle for future marine research efforts. It highligts difficulties may be expected in measuring and quantifying ecological information within OWFs. In this difficult-to-reach environment, where climatic and oceanographic conditions can be extreme, numerous variables are difficult to control, causing measurements to be nearly impossible to standardise. Hence, this case study set out to explore the best research practices under these fieldwork constraints. The next section interprets the reliability and possible biases that surfaced throughout the data collection, processing and analysis of this research. The limitations that were encountered and the lessons that were learned can be used better understand what factors hinder research integrity in the field of OWF marine ecosystems.

However, first, it is worth elaborating on the findings itself. Notably the species richness is similar on the reef substrate and that of scour protection, with sand and cable substrate slightly lower. Both these substrates have a lower structural complexity and therefore can be hypothesised to offer less suitable habitat for species to inhabit. It is suspected that the species richness of the cable substrate, is biased by the CVAT annotation counting method. Every frame is assigned a substrate in CVAT and all species observed within a particular frame are this assigned the associated substrate. Importantly, during the data processing it was noted, that a single frame often contains a transition between multiple substrates. In the case of the cable substrate, it is ikely that the *Anemone* and *Decapoda* species were not spotted on top of the cable itself, but rather on another substrate located straight next to it. This is a considerable bias in the results, and future work should take care to resolve this. For example, by annotating substrate type on a species level not on a frame level. Although this will increase the time requirement.

The presence of *Gadus morhua* can be seen as a success for the nature restoration effort. This species is seen as threatened in the North Sea and an important umbrella species for nature inclusivity in OWFs (Ministerie van Infrastructuur en Waterstaat et al., 2022).This fish species is too rare to appear in the CVAT annotation counts. However the video tallying counts did seem to suggest, though without statistical significance, that *Gadus morhua* favours reef substrate over that of regular scour protection. This makes this study is one of the first to support the theoretical assumption that adding heterogeneous rocks and boulder to OWF scour protection, attracts key target species *Gadus morhua.*

Asterias rubens is the most common *Echinoderm* and *Metridium senile* the most common *Anthozoa.* For the fish, *Trisopterus luscus* is seen to be most abundantly present at each of the surveyed sites. The abundant assemblages of these species all hints at a favourable relationship between these species and the novel marine ecosystem that the hard substrate of an OWF fulfils. *Cancer pagurus* and *Necora puber* appear to be more abundant on scour substrate than on reef and the number of unidentified *Decopoda* appears to be higher on reef than scour protection. This may be due to the video footage being filmed closed to the seafloor whilst surveying scour protection in comparison to the reef. The latter was more structurally complex so the ROV had to manoeuvre further from the seafloor so to not bump into the substrate. This would also explain why *Asterias rubens* appear to be more abundant at reef than at scour protection and *Mytilus edulis* appear more abundant on scour protection than on reef substrate. If the ROV was at a greater distance from the seafloor whenever it was swimming over a more structurally complex substrate, this disproportionately quantified both distinct looking species as well as species that are more camouflaged. The reef contained bigger boulders whereas scour protection, cable and sand substrates where relatively flat. For distinct looking species, such as *Decopoda* and *Echinoderms*, their abundance will have been overquantified at the reef. A relatively greater area unit was surveyed of this substrate compared to the others. Meanwhile the *Mollusca* may have been underquantified at the reef substrate because the camera was too far away to be able to detect individuals properly. This study points out the difficulty with the assumption that the camera angle is a controlled variable surveying a standardised square meter of substrate.

The findings of the case study should be viewed through a considerable fault margin for numerous reasons. First and foremost, a lack of replicas resulted in unfitness for statistical testing and no statistical significance in any of the tests. It is of vital importance to design the experimental set up into replicas of treatments. Here, it was difficult to test species abundance and composition across varying substrates, because species encounters were accumulated across all flightpaths. Instead, the flight path could have been cut up into shorter transects that are substrate specific. Alternatively, camera drops could be deployed at various locations throughout an OWF and record marine life at one substrate at a time. More replicas help to illuminate uniquities between treatments. In this instance, there may have been clearer distinguishments between species abundance and composition across the different substrates, had there been more replicas of each surveyed substrate. Field conditions complicate the differentiation of treatments.

Empirical studies in OWFs measure combined effects to an inevitable extent, because disentangling partial effects of varying pressures is hard in field measurements (Lindeboom et al., 2011). Thus, the values of treatments should be as accurate as possible. Within the CVAT annotation analysis, an improvement is suggested by assigning substrates on a species-level instead of a frame-level. Often the camera frame contained more than a single substrate. By assigning species their respective substrate based on the timing of the substrate changes, an overgeneralisation was made to those individuals that existed in the transition frames, which was particularly common for changeovers to and from the cable substrate, which never occupied the full camera frame. It may be more time consuming to accommodate this improvement, though it is likely to improve the integrity of the species encounters per substrate.

Fault margins of monitoring marine life in OWFs can further be minimised with logistical improvements. It is strongly recommended to focus efforts on best timing the tidal currents, due to their influence on visibility. It is suspected that the poor visibility encountered at turbine B2 will have caused underrepresentation of individuals present here. The high costs associated with marine research in OWFs, motivate utmost preparation. Arguably, careful tidal planning within the boating logistics of the fieldwork yields the highest improvements in the data's visual quality. Instead of, for instance, upgrading the camera system. The GoPro footage in this study was excellent at turbines D1 and D2, where the visibility was good, and the surge and currents were weak.

The results sections outlining the species abundance as recorded by two different counting methods illustrated just how much discrepancy can arise from processing the same dataset through two different approaches of counting. The former, more time consuming and thereby suitable for uncommon species, prompting precise counts. The latter, relying only on a subset of the video footage, often underestimating the presence of individuals and sometimes inferring the absence of a species entirely. Here it is advisable to determine, prior to commencing in a counting method, at what granularity of image intervals are species neither underrepresented nor unnecessarily excessively precisely documented. Furthermore, a distinct advantage of counting observations in annotation software such as CVAT, is its ability to upscale to (semi) automated annotations over time. Annotated images and their respective annotated objects, marine species in this instance, can be used in image recognition and object detection modelling. Objects with large amounts of unique annotations, such as *Asterias rubens* and *Metridium senile,* can be used to train machine learning algorithms. They can be trained to recognise patterns in their colors, shapes and textures to identify objects with matching values across these parameters and automatically suggest label assignments (Augmented AI, 2023). This has the potential of vastly increasing the scale and time requirements of monitoring marine habitats with ROVs. This is of great use in OWFs, which are otherwise expensive to carry out marine research in.

It is possible that miscalculations were made in estimating the square meterage surveyed per substrate and at every turbine location. The intention was set that at any given time the ROV would be swimming at one meter distance from the substrate. This would support the assumption that the length of the flightpaths could be multiplied by a transect width of 1 meter to attain the surface area surveyed. However, upon inspection of the video footage, the ROV did not always seem to manage to keep a set distance from the substrate. It was possibly being pushed further or closer by currents, or due to an inability to adjust its swimming depth to adequately manoeuvre around more structurally complex substrates. Consequently, the flight path width was not constantly 1 meter. It disproportionately inferred the species per area unit metric. The technical specifications of the ROV used and the flying capabilities of its pilot, can play a role in improving this inaccuracy.

Table 11 is a summarised version of Lengkeek et al. (2017) overview of existing methodologies for below surface marine biological research at OWFs and their associated metrics. These predominantly include the operation of rigs with camera, sensor or sampling instruments attached. Lengkeek et al. (2017) also describe various means of in-water data collection aided by SCUBA. However, due to strict safety regimes OWF operators rarely allow for diving activities with OWF site boundaries. Despite shortcomings identified in this case study, it must be recognised that usage of an ROV with video camera, is in practice a preferred means of conducting marine research in OWFs.

Table 11. Overview of existing methodologies for below surface marine biological research at OWFs, simplified from Lengkeek et al., 2017

Marine biology data collection method in OWF	Metric
Acoustic ground discrimination systems (ADGS) survey	Substrate distribution; Habitat/community distribution
Drop-down video/photography	Distribution of habitat/community/biotope; Presence of specified species; Maintained presence of priority species at specific locations
Remotely Operated Vehicle (ROV) video/photography	As above
Grab or core sampling	Species abundance per unit area; Species richness; Diversity indices; Community composition
SCUBA diver core sampling	As above
SCUBA diver video/photography	Broad community character and substrate condition
SCUBA diver transects (visual survey)	Semi-quantitative species abundance (MNCR phase 2 surveys); Biotope presence and distribution
SCUBA diver quadrats	Species abundance (individual abundance or % cover); Species richness/diversity; Abundance of selected conspicuous species
Airlift sampling	Species abundance per unit area; Species richness; Diversity indices; Community composition
Net scrape sampling	As above
Shrimp trawl	Species abundance and weight per unit area; Species richness; Diversity Indices; Community composition
Triple-D dredge	As above
Baited Remote Under water Video (BRUV)	Presence/absence large mobile species

The basic units of an ecosystem are species populations with their biological characteristics (Dannheim et al., 2020). The metrics expressing such ecosystem units as can be measured in OWF compatible field methodologies include species abundance, presence and absence and in some instances the possibility to calculate species richness and diversity indices (table 11). Specific biological characteristics and ecological traits are not easily captured with above listed methodologies. Though more generic ecosystem features such as distributions of substrate, habitat, community and biotope can be observed through these study methods. Empirical studies in OWFs measure combined effects to an inevitable extent, because disentangling partial effects of varying pressures is hard in field measurements (Lindeboom et al., 2011).

From both industry and governmental stakeholders, there is a growing desire to express ecological impacts and their enhancements or mitigation solutions into standardised units of ecosystem valuation. With the available metrics of marine ecosystem measurement in OWFs, the Net Positive Impact (NPI) on biodiversity can in theory be calculated for OWF projects. NPI is achieved when actions taken to a) enhance positive impacts, b) avoid and reduce negative impacts, c) rehabilitate affected species and d) offset any residual impacts outweigh the remaining negative ecological impact (IUCN, 2015). However, pragmatically a ranking of nature inclusive solutions based on their NPI alone is incomplete, as cost efficiency is key to both policy makers and parties placing tender bids. Hermans et al. (2020) includes a cost analysis of all nature inclusive solutions described in their catalogue, where based on a reference wind farm of 60 monopiles, capital investment cost (CapEx) are calculated. As of currently the ecological influence for most on-market nature inclusive solutions have only been estimated based on assumptions on densities and biomass. This is due to a lack long term-monitoring data of nature inclusive measures and their influence on ecological impacts of OWFs (Pardo et al., 2023). This is sorely required to validate theory-based predictions and thereby uncover which nature-inclusivity measures are most effective and suitable.

6. Conclusions

This study offers a comprehensive overview of the solutions that can be implemented in the design and planning of an OWF to mitigate its negative ecological impacts and enhance the positives. Touching on both infrastructural design options and planning considerations, a wide palette of nature inclusivity solution found. By incorporating the TRL of solutions and identifying their mitigation hierarchy status in relation to the ecological impact they solve, this study aimed to evaluate the relevance and effectiveness of nature inclusivity for OWFs. Analysing the TRL of nature inclusive solutions, it could be determined if ecological impacts can currently be resolved, will be resolvable, or currently have no prospect of a resolution, i.e. whether nature inclusive solutions are on-market, in development or missing.

On-market solutions to ecological impacts of OWFs, include numerous noise reduction techniques for pile driving monopile foundations, to minimise acoustic disturbance to marine mammals and fish; Minimising bird and bat collisions by migration-based or object recognition curtailment, reduced offshore lighting or altered onshore line configurations. As well, available for immediate deployment are a wide range of artificial reef structures, each brand with a unique twist on the concept of structural complexity and hard substrate restoring marine habitat with its placement. The most effective solutions that can currently be implemented, with proven mitigation effect, are those avoiding an ecological impact entirely, instead of minimising or restoring it. These impact avoiding solutions are clustered into the realm of site selection and micrositing therein, to geographically avoid OWF development on and near ecologically valuable habitat.

A great number of nature inclusivity solutions were found to be upcoming and in development. Within noise mitigation, installation methods are underway that absorb pile driving sound, as well as foundation installation techniques that do not produce sound in the first place. Such jetting and Vibrojet® technologies are therefore more urgent to fund and develop from the mitigation hierarchy perspective. Placing all ecological impacts of OWFs into one tabular overview, made it abundantly clear that there are numerous hazards, risks and unknowns that cannot be completely mitigated yet: as not all ecological impacts have an avoid solution. This means NPI, which many claim to strive toward, is currently unachievable within OWF development, without biodiversity offsetting any residual impacts outweighing the unmitigable impacts. Biological offsetting, as a solution in and of itself, is yet to be incorporated into standardised use in this sector.

It was found that for floating turbines, which are projected to increase in market share, there are few novel solutions to this type of foundation. Instead, there are slight nuances in the ecological impacts of floating turbines, compared to bottom-fixed turbines. Predominantly, the absence of pile driving sound is a major benefit to marine fauna. However, further research should test the hypothesis that the scaping mooring lines of floating turbines, may decrease their suitability for benthic restoration efforts. Other forecasted ecological opportunities as well as ecological threats relate to OWFs co-location with aquaculture. Hanging cultures of extractive species, such as mussels, could form a natural, sustainable influx of $CaCO_3$ into the system theoretically stimulates skeleton growth. However, fed aquaculture or passive fisheries should be well regulated as they do not necessarily enhance ecosystem functioning. It is recommended to not lose sight of OWFs original artificial reef effect and reserve effect.

Another promising novel direction that is being taken is to emphasise reintroduction of reef-building species, such as European flat oysters. Remote settling of spat onto scour protection, is seen as the most scalable of oyster restoration solutions, as it can be incorporated into the base case design. Besides scalability, nature inclusivity has recently shifted its focus onto the need for locally sourced and unprocessed, natural materials be used in habitat restoration. There are various patented habitat restoration products on market as well as in development, such as mesh nets and flexible matrasses, that do not adhere to these characteristics. Moreso, the small scale of artificial reef units does not impact fish assemblages at a population level, thereby questioning the value added from continuing their development. The expert interviews agreed that adding heterogeneous calcareous rocks to the base case scour protection is the most cost-effective solution to support marine ecosystems at the largest possible scale within OWFs. Arguably, habitat restoration and the creation of structural complexity is thus far understood within the research landscape of OWFs, that emphasis should be deviated away from this issue and amplified onto those ecological impacts that are yet to be solved.

It was found that many missing solutions are those relating to ecological impacts, of which the extent is yet to be understood, let al.one how to mitigate them. Knowledge gaps in ecological impacts of OWFs crystallise immediately when zooming out and looking at the future prospect of large-scale developments of OWFs and their long-term deployment in the ocean space. Beyond the assumption of increased future vessel traffic and associated fuel pollution, it's unknown what cumulative impacts of OWFs have combined with other maritime users and whether these will surpass ecological thresholds. Studies are yet to commence to model and monitor the likeliness of OWFs to serve as biofouling stepping stones. The hydrodynamic and metocean impacts of OWFs are majorly understudied, leaving it unclear how large scale OWF development will alter stratification patterns and ocean currents. Will stratification patterns be altered? As for the trend of co-locating offshore hydrogen with OWFs, the highly toxic discharge water of the cooling systems, theoretically impacts marine functioning negatively, but an environmental impact assessment is yet to be completed. These underexposed unknowns are a true blind spot for nature inclusivity in OWFs. This study argues that there is a discrepancy between nature inclusive innovations being developed and ecological impacts that most urgently need addressing. This may be because the former are too complicated or unpopular to pitch, showcase and fund.

In pursuit of testing measurement and quantification methods for marine research in OWFs, the HKZ case study complements this research with valuable reflections on best practices. With the logistical complexity and the steep costs of underwater monitoring in OWFs, this proof-of-principle set out to explore how to best conduct standardised data collection under the extreme field conditions found in OWFs. It was found that numerous variables are difficult to control, thereby affecting the integrity of the data. Of particular importance, is to design the field monitoring, like an experiment with multiple replicas per treatment. This would have increased the possibility of attaining meaningful output in the statistical testing of the differences across substrate types. Furthermore, the proof-of-principle demonstrated the possibility to upscale to automated data processing, such as semi-automated annotations in a platform like CVAT. Despite shortcomings identified in this proof-of-principle study, it must be recognised that usage of an ROV with video camera, is in practice a preferred means of conducting marine research in OWFs. Hence, it can be concluded that with careful experimental design this methodology, in combination with the prospect of automating image processing, offers a promising means of surveying marine life in OWFs.

To date, the effectiveness of most nature inclusivity solutions in mitigating certain ecological impacts, are estimated based on theoretical assumptions. The case study of HKZ is one of the first to respond to the dire need for empirical evidence to validate nature inclusivity success. The footage collected in HKZ provided a valuable initial insight into the benthic and pelagic species present in this section of novel North Sea ecosystem. No statistically significant differences were found in the species composition of the four prevailing substrates: scour protection, reef, sand and cable. Notably the species richness was found to be similar on the reef substrate and that of scour protection. Umbrella species *Gadus morhua* appeared to be more abundant on reef substrate than any other, although this should be verified with more replicas to statistically test. This hints at effective habitat creation for a threatened umbrella species, by means of adding heterogeneously sized calcareous rocks on top of scour protection.

Final remarks

This study reveals there is good reason to be critical of nature inclusivity in OWFs and a need for it to readjust. However, it must be stressed that these critical remarks this study are not meant to lobby against offshore wind energy. With increased and more uniform windspeeds over sea than over land, OWFs provide a reliable means of energy harvesting than their onshore equivalent and more importantly, face less social resistance and space scarcity (Belu et al., 2017). Offshore wind, after nuclear power is the safest and cleanest source of energy, as measured respectively by their accident and pollution-rated death rates and lifecycle emissions (Ritchie, 2020). Yet OWF has unmatched cost-effectiveness and rapid deployability potential compared to nuclear (Carabott and Will, 2024), and no risk of radioactive catastrophes. Relative to other sources of energy, OWFs are thus widely regarded as the most credible and scalable strategy for a resilient and decarbonised energy supply (Galparsoro et al., 2022). Thus, this study encourages stakeholders across the sector to make meaningful improvements where they can, to assure nature inclusivity in OWFs continues to progress into a proven and science-based vehicle of nature protection and enhancement.

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Appendix 1. Interview questions and answers

Interview template

Introduction (10 minutes)

Thanks for participating and taking the time

Introduce myself, my research project, the framework of nature inclusivity in OWFs

Why the interview

The interview will not be recorded but I will be taking notes

The identity of the individual and their employer will remain anonymous in publishing outputs of this research

If interested I can share and present my final work with you

Interviews questions

Can you tell me a bit about job description to understand the context in which you work with nature inclusivity in offshore wind? What's your area of expertise?

What nature inclusive technologies do you know about that you are in favor of? What are the advantages to the marine ecosystem? Wat is the ecological impact that they address? What are the technological readiness and the mitigation hierarchy status of these new technologies?

What nature inclusive building techniques or requirements are the most effective? Which ones are best value for money? What are the most effective ecological mitigation strategies? What sort of restoration projects or reintroduction techniques are most effective do you think?

Are there nature enhancements that you can do elsewhere in an OWF apart from the scour protection? For example, around the foundation? The tower and blades? Elsewhere in the park or outside of it?

Can you list nature inclusive solutions that have come on the market more recently? In the last five or so years? The ones that aren't already described in the Hermans catalogue, like the fish hotels, 3D structures and cable matrasses. What is new?

What can policy makers and regulatory bodies do to most effectively mitigate ecological impacts and stimulate nature restoration in OWFs? What role do you see for marine constructors, NGOs and startups? How responsible are OWF developers or should the responsibility be shared more?

To what extent are nature inclusive solutions adapted to trends in offshore renewable energy infrastructure? Like for example, floating wind turbines instead of bottom-fixed? And the presence of offshore energy hubs or combined renewable energy technologies like hydrogen?

In light of large-scale expansion of OWFs and their long-term deployment in the marine space, how much does nature inclusivity in OWF, take into account the incidental ecological risks and uncertainties of this trajectory? For example, cumulative effects and species invasions, are there solutions being developed for these ecological impacts?

What risks are there in creating nature inclusive designs in OWFs? For example, cumulative effects and species invasions, are there solutions being developed for these ecological impacts?

Which area of nature restoration and enhancement in OWF is the most understudied or poorly understood? What ecological problems do you think are most pressing in the offshore wind sector and most urgently need addressing in the form of a nature inclusive design solution?

Closing remarks (5 min)

I have asked everything I wanted to ask, so we are reaching the end of the interview. Thanks again for taking the time.

I will send you my final thesis when it's done and assure your identify and that of your employer will remain anonymous.

Have a nice day!

Interview summaries

Interview #1

Date: 12/11/2024
Location: online
Stakeholder profile of interviewee's employer: Offshore marine contractor
Function of interviewee: Specialist coastal and marine ecosystems
Area of expertise: Nature inclusive landscaping and species rehabilitation projects in OWFs

Notes:

- The best solution to incorporate nature in the wind farm landscaping. To design solutions within the design of the wind park, not as add on or standalone structures. Rather as part of the build. To use the foundation rock material and make it different heights and sizes to create more habitat complexity whilst functionally it remains scour protection.
- We shouldn't focus so much on 3D printing all sorts of cool structures, those are more interesting for recreational divers, which you don't get in offshore wind parks. So, there's no use in printing these blocks that have a large carbon footprint as there are made from new cement material instead of natural materials. Also, a lot of these concrete structures have toxic materials leaking from them over time, from being so processes so that's not good for the environment.
- Cages attached to the foundation, like fish hotels, have no influence on the fish population, they are way to small scale. So, these aren't the best resolution for nature either.
- The best solutions are the ones that can be applied at the largest scale possible. Ideally sour protection including materials rich in calcium carbonate such as limestone and marble, because these help skeletal construction of species.
- Instead of dumping a bunch of shell material, which is high in calcium carbonate but immediately washes away, you can add vertical mussel reefs, which are hanging cultures that gradually and sustainably deposit shells over time feeding the habitat below. A Belgian project called Coast Busters is doing this.
- It's also very important to focus on renewable or recycling materials, because it's not good for the environment to extensively process rock material when you can just get it from the quarry directly. Not sure if this is done in offshore wind yet but for break waters for example it is common to repurpose material that has previously been submerged which thus already has marine life growing on it. This then grows into more elaborate marine habitats than when using brand new material.
- For floating turbines nature inclusivity could focus more on the water column instead of benthic life, because they for much deeper waters. So here mussel or seaweed structures could be beneficial for both passive aquaculture and advancing marine life in the water column.
- Upon disassembly what you could do if you did have to remove the entire scour protection, which is full of life after 30 years, is relocate it to the next scour protection of the next wind park. Leaving it is better of course, but this is not allowed then it would be better to relocate it to a designated nature area, so it doesn't all go to waste. The discussion on what to leave and what to tidy up at the end of life of a park, needs more attention

because at the moment the permits say you have to clean everything up, but it's not necessarily best for nature, now that you have new hard substrate facilitating new benthic life.
- Besides landscaping and adjusting the existing infrastructure to optimally facilitate nature, it is also important to focus on reintroduce some marine life. In the Netherlands we focus on Oyster rehabilitation because they originally existed in large reef colonies in the North Sea. Sea grass for example is too deep.
- For Oyster rehabilitation you can crane adults on a large structure to the seabed. Or manually instal a small structure with adults or you can have spat, which are young oysters and settling larvae, on the scour protection directly. This last option is called remote settling and seems to be most scalable if it can be done correctly. You can't just place loose oysters because they will wash away.
- The oyster rehabilitation is not suitable everywhere in the North Sea and should focus on the areas in the North off the coast of Groningen where there were oyster reefs originally. Its not as suitable to do this near The Hague for example, it doesn't work there.
- It's also important to group nature efforts and not do scatter mini projects all across the North Sea. Policy makers should create target areas for specific nature goals and not want to do a bit of everything everywhere, because when for example oyster restoration efforts are too fragmented, they don't work. And if they are done in the wrong place, it doesn't work either. Area wide planning, not park specific planning, is needed.
- Pilots are still important, but in the end, solutions must be scalable to be of any benefit to the ecosystem.

Interview #2

Date: 14/11/2024
Location: online
Stakeholder profile of interviewee's employer: OWF operator
Function of interviewee: Offshore wind energy consultant
Area of expertise: Environmental permits for OWFs and impact assessments and monitoring requirements for OWFs

Notes:

- A major contribution of our work has been in nature monitoring programmes, which is an important element of getting permits. If you don't measure you don't know what is there to protect. We have done monitoring on birds with radar techniques and on marine mammals, such as porpoises and seals, with passive acoustic networks.
- Bird migrations need to be modelled accurately to best predict when to curtail the wind turbines, you can't decide to curtail on the spot but need to inform the grid operator two days in advance so it's important to have a good estimate on when there are most bird migrating. This varies per wind park location and is hard to measure accurately for that location.
- Most birds aren't stupid and won't fly into noisy hazardous objects, but when birds are over sea on migratory routes their sole focus is to get to land, and they are in survival mode and it's dark at night so sometimes they are attracted to the lights on wind turbines thinking they have reached land.
- In monitoring birds, it is hard to detect which species they are, but you can get reasonably accurate counting's and flight direction, so once you have monitored for a number of migration seasons you can try to make a guess for the next year when to curtail to get the least collisions. But you can't curtail all the time so it's very difficult to select the right hours of the right nights to do this.
- And even the radar technology used to count the birds is sometimes not completely accurate because there can be noise in the radar, like for example if its very windy of the waves are really big then the radar quality isn't good for counting birds.
- The first tender round in the Netherlands only required developers to meet environmental impact mitigation measures, but the second and the third round have non-price tender criteria for nature enhancement, so in the newer parks there is a lot more attention for not only nature protection but also nature enhancements.
- In the older parks therefore, the focus is on monitoring what happens naturally. Naturally the scour protection already creates reefs as long as there are no bottom disturbing activities like trawling fisheries. That's why the

North Sea is a desert, because we overfished it. Now it's restoring even though we don't really do anything. So, for nature a key solution is to not disturb it and regulate bottom-trawling.

- I am very sceptical of all the funky shapes and beautiful designs that you can now score point within tenders. Fish don't care how cool the substrate looks; they just want calcareous rocks.
- Our initial oyster restoration project didn't work out because we reintroduced lots of adult oysters, but they all washed away, we are now collaborating with NGOs to do this for us, as they are more knowledgeable on the topic, and they will try new things like remote settling and doing research with spat collectors. We need to do more monitoring before we know what solution we can implement not on a single turbine but the whole park. I think the collaborations are important for the research to be independent, instead of us doing our own assessment.
- Bat behaviour is understudied in wind parks, I'm not sure if they like the turbines as resting places or if we disrupt their natural behaviour. Same with cormorants, who breed on platforms. Is it a good thing or a bad thing? There is lots of fish here and no predators, so it's a good new breeding area, unless there are still suitable breeding areas onshore, then its disruptive.
- The most important solutions for nature in offshore wind parks is better monitoring otherwise we have no idea what measures are best to take.

Interview #3

Date: 18/11/2024
Location: online
Stakeholder profile of interviewee's employer: Energy company (OWF developer and operator)
Function of interviewee: Marine ecology specialist
Area of expertise: Ecological tender criteria and biodiversity strategy for renewable energy sector to make a net positive contribution to nature

Notes:

- We develop strategies to make a net positive contribution to biodiversity. This is more difficult for birds, but underwater it is relatively easy in absence of fisheries, lots of life automatically develops on hard substrate that is introduced with the placement of scour protection. Passive restoration of the seafloor, by minimising bottom-trawling fishing, is very important for any active restoration to have a positive impact.
- Restoration projects don't have to be very quirky ideas. Startups sometimes forget that the best innovations should fit into the existing base case design and should be scalable. A scour protection engineer on the other hand knows that the density of the design is more important than its weight.
- Its good for restoration efforts to be area specific and for designs to start with the question of what restoration task is required here. This can be based on the policy target species, such as Atlantic cod in the Netherlands for example, or on generally increasing the ecological capacity of an area. Its important to define how big the mismatch is between the present state of an ecosystem and the target state. By mapping all the stressor/receptor interactions (i.e. the ecological impacts and the impacted species), you can best decide what nature inclusive are suitable for implementation.
- Remote settling of oysters is a very important novel restoration technique, which entails biological loading (of larvae) onto regular scour rocks.
- In Belgium there's a wind development lot on gravel beds which is a Natura2000 habitat, here it would make sense for nature restoration efforts to attempt to mimick this naturally valuable habitat.
- In lots that are tendered in particularly quiet areas, for example, further away from shipping routes, it would make sense to put more emphasis on maintaining the silence.
- By taking more of an ecosystem approach instead of focussing on individual species, you take into account the broader ecological functioning. For example, also plankton and primary production. Policy makers unfortunately focus mostly on the big 'huggable' species, like marine mammals. However, smaller less

visible species at the lower trophic levels are just as important to protect and conserve. Or tube worms for example are good reef builders.

- The government should determine who takes responsibility for which components of marine restoration in offshore wind parks. Wind farm developers for example only have a mandate directly around the turbines. The area in between turbines is outside of our zone of influence. So regulating bottom-trawling for example is a nature inclusive solution that developers legally can't do.
- Developers are happy to implement nature positive measures, it's not something that will make a business case unviable. However, there is a need for clear directions because businesses will only do what's required of them and won't just start a marine park if no one has asked for that. It works well though to subscribe outcome-based indicators in tenders, instead of input based norms. For example, to instigate noise thresholds that cannot be surpassed and leave it up to the developers how to go about obliging to those thresholds. Using ALIs (acceptable level of impacts) leaves room for the developer, to determine which low noise installation method is most effective and cost efficient. There are good hydro dampers and pulse cushions for bigger turbine models which minimise sound, but its better to avoid it entirely. Abaitment is not enough to respect the noise thresholds. There's a jetting technology being tested, which makes the substrate fluid and then penetrates the monopile, which is currently expensive but hopefully eventually all monopiles are installed in this way.
- Also developers shouldn't do all research and monitoring on their own, but instead collaborate with NGOs and research institutions, to assure the findings are independent and impartial.
- Whilst floating turbines don't require as much noise in their installation, there is a possibility that the chains of the anchors create a noise at another tone, which may disrupt marine mammals and cause new ecological problems or masking behaviours. This is understudied.
- Biological offsetting isn't really a thing in offshore wind, you could do it for birds. For example to offset the bird mortality of blade collision, and have developers pour into a bird restoration fund, centrally managed government and spent on maintaining important breeding areas.
- The cumulative hydrodynamic influences of offshore wind farms are understudied. The joined impact on ecosystems from hydrodynamic changes like stratification, turbidity, currents, primary productivity. Deltares has started a monitoring programme on this, but it is all still very much in the research phase even though it is a reoccurring concern. Harvesting so much of the wind at sea probably has a local influence on weather patterns, but modelling this is much less of a digestible and tangible topic so it gets less attention.
- Invasive species in the North Sea are hard to control, because due to climate change there are a lot more displacements of species. For wind parks it may not be a big problem if new species are introduced, as long as they aren't in the way of the ecosystem functioning. And we shouldn't forget that before wind parks, there was already a lot of new hard substrate introduced into the sea from oil and gas platforms and shipwrecks, so these are already functioning as stepping stones.
- The question is whether its necessary to maintain the original state of the North Sea, it may be better to assure we rebuild a resilient new ecosystem, with many niches, healthy populations, passage routes for birds, sustainable food webs and reef building species. But this will be a new reality for the North Sea not a return to the past.

Interview #4

Date: 20/11/2024
Location: online
Stakeholder profile of interviewee's employer: NGO
Function of interviewee: Project lead nature-friendly offshore wind
Area of expertise: Ecological risks and opportunities of OWFs and policy requirements for nature-friendly OWFs

Notes:

- What's important is to prevent and minimise risks and only then look at strengthening opportunities for nature, or offsetting risks. We use the mitigation hierarchy in our work. I find it important to first make it clear how bad marine ecosystems are doing, so to first minimise further impacts in wind parks. In my experience lots of wind developers want to jump to restoration because it's more fun to show and communicate to the public.
- It's good that there are startups testing the effectiveness of different solutions, but what we already know is that heterogeneity of rock size in the scour protection is very effective. The nature strengthening potential really is in the scour protection, not so much the foundation and attaching bio huts to it. There's no artificial reef effect on the foundation, it's on the scour. A lot of the startups have a shiny story, but not the best product.
- Mitigation noise pollution is probably way more important than fixating on the shape of artificial reefs, but it is harder to sell and make it sound interesting so it gets less attention than it should.
- Another solution that is being tested to reduce bird collisions is to add more color contrast to the turbine blades, by painting them with stripes. But these color changes also have thermal influences on the build of the blades and turbine producers like Vestas won’t guarantee the safety of the turbines if you paint them as you like.
- Orsted has tested a quiet installation method, called jetting, which is where they make the seafloor fluid so its less noisy to get the foundations in. However, it's still a test, so it might not work on all substrate types and ocean conditions, so it's still a long time coming until this solution is ready for all new turbine installations. As with all the other silent installation methods.
- There are experiments with water replenishment holes, which are meant to provide shelter to species and additional hard substrate on the inside to attach to, but their effectiveness is still being tested. A lot still has to be tested, more monitoring has to be done in general.
- For minimising bird collisions, all the solutions are still in a concept phase as well. There are lots of camera systems in development to track how birds behave around wind parks, but we need to do more monitoring to get a better understanding of this. Start-stop programmes are difficult because we only have data of a few migration seasons to use as input for the models that will predict when to curtail. And all parks are different migration routes so if you have a model that works for one park, it could be rubbish for another one and the model won't be accurate at all, in telling you when to best curtail.
- I would recommend for policy makers to look at light pollution as well, at night, the lights on wind parks can attract birds and changing your light design can minimise this, but the maritime safety protocols don't allow it, so more flexibility here would help. Acoustic deterrents are used to chase away birds but it's better to prevent and avoid further influences instead of battle impacts with more influences.
- Multi functional use of marine space is a risk for nature because it will be getting more crowded and require more resources to be shared. As a solution for this I propose more international collaboration, like an international master plan for where to allocate energy, fisheries, nature. Marine spatial planning and strategy should be done ocean basin wide, not draw the lines of per country, it doesn’t work like that for the ecosystem.
- The presence of hydrogen electrolysers at sea brings completely different changes, mostly local water temperature increases, because of all the cooling water required for hydrogen energy production. Could easily make local water 5 degrees Celsius warmer in temperature, but maybe this doesn’t matter on the larger scale, it’s unsure. Hydrogen has to be compressed to be transported to shore so there is sound pollution there as well.
- All the pressures from the different maritime users have synergised effects, which could strengthen one another. Wind parks at large scale may have stratification impacts on the water, the placement of turbines in the water causes continuous mixing of the warm top layer and the colder water at depth, which is unnatural and means that primary production in the top layer is disturbed. This effect may be strengthened if floating solar is developed at large scale, maybe there is an additional decrease in primary productivity, because no light penetrates through the water. With amplified mixing from the presence of the turbines there will be less primary productivity.

Cumulative effects of the mixing caused by the presence of turbines isn't clear on seasonal stratification and destratification patterns. Not yet studied at this scale. But changes in hydrodynamics seem plausible. The effects of less available nutrients and light on higher trophic levels is unclear. Not yet studied at all.

- In the sector sometimes people say why do we have to enhance nature we already did an environmental impact analysis? An alternative that I heard of recently, is to do an environmental outcome assessment. Instead of looking at the impact of your activity and how you will mitigate, you approach it by envisioning what you want the ecosystem to look like at the end and design what kind of minimisation, restoration and offsetting is necessary to get to this healthy eventual ecosystem.

Interview #5

Date: 20/11/2024
Location: online
Stakeholder profile of interviewee's employer: Energy company (OWF developer and operator)
Function of interviewee: Marine ecologist
Area of expertise: Ecological permit requirements for new OWF tenders and ecological monitoring requirements for operational OWFs

Notes:

- It's important to try and design a wind park with positive ecological influence beyond its own lifespan. So we try to kickstart nature and over time let it grow on its own. We try to generate biogenic reefs on scour protection and then just leave it to develop. Importantly there should be no bottom disturbance, so only passive fisheries.
- Artificial reefs are very hip and popular at the moment, but its better for nature to have a variation of rock sizes in the scour protection and focus on implementing this at a park wide scale, not at the base of a single wind turbine. Nature restoration should be integrated in the design of the park and not be playround-type add-ons.
- There's also a lot that still can be gained from optimising the turbine layouts, within the designated lot. It's not yet common practice but, for example, you can do your micro siting so that in sand golf habitats you avoid construction on ecologically sensitive areas.
- We do some oyster restoration projects, mostly settling larvae on substrate, by integrating it on the scour protection. An important realisation that we have had, is that oyster restoration is not necessary logical everywhere in the Dutch North Sea and should probably focus on those areas where they naturally occur the most, such as the coast north of the province of Groningen.
- For export cables, eco matrasses may not be the best solution because they cover such long distances, it wouldn't be viable to implement such a delicate solution. Cable crossings are complex because they need to be safe for fisheries as well. The cables themselves, because they are below the seabed, aren't always tidied up at the end of life, so this could be better enforced by governing bodies to avoid marine trash.
- Besides scalability, another important recent focus is degradability. There are more initiatives now to work with natural materials. For example, Van Oord created the GeoWall, which is made of sediments. There's also something called BESE (Biodegradable EcoSystem restoration Elements) made of potato starch leftovers, which is used for salt marshes and mangrove restoration, but might be applicable to offshore wind.
- It is important to be location-specific when defining nature restoration and deciding what ecological functions you want to stimulate. In some places there already is a lot of hard substrates for example. In some areas the nature values that are present are very different than in others.
- Before nature restoration planning and design, we need to focus on avoiding negative impacts in the first places. For example, its better to focus on silent installation methods, rather than bubble curtains which hide the pile driving noise with bubble noise. It will take a long time before all monopile installations will be without noise pollution, as the technologies for this are all still in testing and piloting stage. For some technologies the limited factor is that there are no noise regulations yet, for example vibrating installations, its unknown how

those acoustics travel through the water column and on what spectrum, so the government is hesitant to permit it, because they don't have rules for it yet.

- With bird mortality as well, we don't know yet what the scale of the mortality is and the influence on populations. There's more and more research underway which may indicate the collision rates aren't that bad. For this reason, we need to continue to do valid monitoring, so we don't base our solutions to environmental impacts on assumptions that are wrong.
- To some extent environmental impact assessments have gone overboard compared to other sectors, like oil, gas and heavy industry, these are bad for species on both local scales but also global, because of their contribution to climate change and global warming. So sometimes the strict environmental regulations seem disproportionate for wind energy, which is among the best solutions for emission-free energy. The ecological impact of a coal plant is much worse than that of a wind farm, but it is much easier to visualise how a bird flies into a spinning turbine, than it is to visualise how a bird population is affected by greenhouse gasses.

Interview #6

Date: 22/11/2024
Location: online
Stakeholder profile of interviewee's employer: Grid operator
Function of interviewee: Marine ecologist
Area of expertise: Nature inclusive cable design and the influence of electromagnetic fields on marine species

Interview notes:

- There is more than 4000km of cables in the Dutch North Sea by 2030 with 90 cable crossings. The electromagnetic fields of these cables have an influence on marine species, which is being studied.
- Most cables are below the seabed with rock dump on top. When cables cross one another by default they create a structure that is the right shape and size for filter feeders to grow on. So cable crossings are very suitable for reintroducing for example oyster reefs.
- It's important to design cable crossings with calcareous material with various gradations of rock sizes. Most importantly the reef effect has to be scalable, rolled out on a large scale, for it to be useful.
- In the lab, oysters settle and grow on calcareous material, but in the North Sea this is difficult, possibly due to the rougher conditions. We are now testing a technique called outplacements, where oyster larvae are grown on rocks in the lab and later used in the North Sea as cable and scour protection. So the rock material used for the cable and scour protection is loaded with oyster spat, but it is part of the infrastructure itself, it's not a small standalone reef, which wouldn't be as scalable.
- The use of eco matrasses is more for pipelines than electricity cables. This is because an offshore export cable is only about 30cm in diameter so if you want to cover it with an ecomatras, you will still also need to cover it with rock material for it to be stable to the seafloor, so you might as well only cover it with rocks.
- In some areas eco matrasses may be more suitable, especially if they can be produced with natural materials.
- Another important nature inclusive measure that should be taken into consideration with regards to offshore cables is the disassembly. Most of the cable materials themselves can be recycled very well, because they consist of aluminium and coper. When they are retraced from the sea floor it can quite easily leave the reef that has started growing on the rock material intact, because you just pull out the cable from underneath. However, there is a liability concern there, because policy regulations as of currently require us to tidy up everything we built in the marine environment at disassembly. So you wouldn't be allowed to leave a cable crossing, even though it's turned into an ecologically valuable site. If fishermen get their stuck in the structure that's left behind, you may get the blame. New disassembly policy should be developed to solve this.
- In the past five years the focus within nature inclusivity in offshore infrastructure has shifted. Initially everyone wanted to add as many artificial structures as possible, like reef ball and so on. Now, there has been a realisation that we don't want to just keep adding hard substrate but minimise our interference with nature and just best utilise the offshore infrastructure that is necessary.

What's new as well is that we are looking at other reef building species, not only oysters. For example, *Sabellaria* worms. We learned that Sabellaria larvae are naturally still present in the North Sea and as long as there is no bottom trawling they regrow. Therefore, an important nature inclusive measure is still just to limit sea floor disturbance.

- An important under illuminated topic within nature conversation and offshore infrastructure, is the effect of coating. Cables are covered in thick layers of paints. With the quantity of the cables in the sea it's like pouring toxins into the marine environment. There should be more research on the composition of the paint, because there should be variants with less toxic compounds and more eco-friendly alternatives. This isn't as 'sexy' of a topic, hence it receives less attention. On the long term it will have a big influence though.
- Another important development that marine biologists should be involved in more is offshore hydrogen. The antifouling and cooling systems. The cooling systems pump enormous quantities of cold sea water and cause temperature changes to the sea water. The scale of this is unknown, is it only local or will it have a larger scale effect on the long term? The discharged water is also full of anti-fouling chemicals, which are very poisonous to the ecosystem. These systems are being designed as of currently and should contain more input for how to cooperate with nature.

Interview #7

Date: 26/11/2024
Location: online
Stakeholder profile of interviewee's employer: Research institute
Function of interviewee: Marine biology researcher
Area of expertise: Net positive approaches and design for coastal hard works and functional analysis of benthic communities

Notes:

- In Norway there's a big push for floating wind and thus a need to understand nature positive approaches around those foundations that aren't fixed to the bottom. However there is a lack of long term experiments and especially the knowledge of nature inclusive design in floating wind turbines is limited. It's all still very new.
- The best thing to do for floating wind, seems to be, not to start from scratch but try to repurpose nature inclusive solutions that were invested for fixed bottom turbines and make them work for floating. For example, can we include oyster restoration. But this still must be tested in situ and monitored long term, to know if it would work.
- One nature inclusive design add-on option that could work for floating is to add lobster cages, to provide them with habitat. Some are sceptical of the efficiency of this idea. It's still at the conceptual stage and will need more research.
- The most important effort that can be made within the domain of nature inclusivity in offshore wind, is for there to be proper tests done, because if there is no baseline information to understand how solutions are impacting the ecological functioning, there is no point advertising them.
- Nature positive approaches should be specific to the needs of the local environment and to the type of turbine. With floating turbines for example, they are located exclusively in deep waters, so often there is no point for strengthening the benthic ecosystem, because its way too dark down there. Then the solution should be focused on the pelagic.
- Not all wind development sites deal with the same ecological challenges and needs. The target species can be vastly different in one part of a country's territorial waters, compared to the next. Some areas are MPAs or high biodiversity, for other areas there is a major concern for species invasions because they can completely alter the whole trophic system by introducing completely different functions to what is native in an area.
- Micro siting is also important because within a wind park there can be ecologically important areas that should be avoided in construction.

The government really must encourage nature positive approaches. Some companies are interested in sustainability topics but need further information, and basically regulations to do the right this. Ecological tender criteria are very new in most of the world outside of the Netherlands and therefore it is important that we also start to develop local knowledge on local needs. Policy and regulations can push companies to do better.

- Some nature inclusive innovations are fine to be designed elsewhere, but it's important to use local materials and not ship everything halfway across the world.

Appendix 2. Raw data of case study

The URL below links to my Google Drive space, which was used to store the raw data of the case study. In this spreadsheet the first tab contains the counts from the CVAT annotation counts, and the second tab includes the video tallying counts:

https://docs.google.com/spreadsheets/d/1zzEyMxSfbi1V8vha2astfGDH0tWhJY6C/edit?usp=sharing&ouid=104336776330016814376&rtpof=true&sd=true

Appendix 3. R script of figures and statistical testing of case study

```
# Packages

```{r Packages, warning=FALSE}
# List of packages to be installed and loaded
packages <- c("readxl","vegan", "dplyr", "tidyverse", "tidyr", "markdown", "car", "vegan", "ggplot2",
"gridExtra")

# Install packages if they are not already installed
install_if_missing <- function(pack) {
  if (!require(pack, character.only = TRUE)) {
    install.packages(pack, dependencies = TRUE)
    library(pack, character.only = TRUE)
  }
}

# Apply the function to each package
sapply(packages, install_if_missing)

library(readxl)
library(dplyr)
library(tidyverse)
library(tidyr)
library(markdown)
library(car)
library(vegan)
library(ggplot2)
library(gridExtra)
```

Load Data

```{r Data, warning=FALSE}
# ggplot1

counts_per_substrate <- read_excel("Final_data_stats_ggplot.xlsx",
                                   sheet = "Counts_per_substrate", col_types = c("text",
                                                                              "text", "numeric",
"numeric", "numeric",
                                                                              "numeric"))
colnames(counts_per_substrate)[colnames(counts_per_substrate) == "Scour protection"] <-
"Scour_protection"
counts_per_substrate_long <- counts_per_substrate_long %>%
  mutate(Substrate = ifelse(Substrate == "Scour", "Scour_protection", Substrate))
counts_per_substrate_long <- counts_per_substrate %>%
  pivot_longer(cols = c(Reef, Scour_protection, Cable, Sand), names_to = "Substrate", values_to =
"Abundance")

#ggplot2

counts_per_substrate2 <- read_excel("Final_data_stats_ggplot.xlsx",
                                   sheet = "ManualCounts_per_substrate", col_types = c("text",
                                                                              "text", "numeric",
"numeric", "numeric",
                                                                              "numeric"))
colnames(counts_per_substrate2)[colnames(counts_per_substrate2) == "Scour protection"] <-
"Scour_protection"
counts_per_substrate_long2 <- counts_per_substrate2 %>%
  pivot_longer(cols = c(Reef, Scour_protection, Cable, Sand), names_to = "Substrate", values_to =
"Abundance")

#ggplot3

comp <- read_excel("Final_data_stats_ggplot.xlsx",
                   sheet = "MethodComparison", col_types = c("text",
                                                             "text", "text", "numeric", "numeric",
```
```

```
"numeric", "numeric"))
colnames(comp)[colnames(comp) == "Scour protection"] <- "Scour_protection"
comp_long <- comp %>%
  pivot_longer(cols = c(Reef, Scour_protection, Cable, Sand), names_to = "Substrate", values_to =
"Abundance")
```

```
# Colour scheme

```{r Colours, warning=FALSE}

# Define the color scheme
substrate_colors <- c("Reef" = "#4CE600",
                      "Scour_protection" = "#1974CD",
                      "Cable" = "#CE00CD",
                      "Sand" = "#FED700")
```

```
# GGPLOT CVAT analysis

```{r CVAT, warning=FALSE}

# Define the desired order for Latin_Name
latin_name_order <- c("Cancer pagurus", "Necora puber", "Pagurus bernhardus",
                      "Decopoda unidentified", "Asterias rubens",
                      "Ophiura ophiura", "Ophiotrix fragilis",
                      "Echinoderm unidentified", "Mytilus edulis",
                      "Crepidula fornicata", "Callionymus lyra",
                      "Trisopterus luscus", "Mullus surmuletus",
                      "Pholis gunnellus", "Gadus morhua",
                      "Pisces unidentified", "Cylista troglodytes",
                      "Metridium senile", "Actinothoe sphyrodeta",
                      "Anthozoa unidentified")
# Convert Latin_Name to a factor with specified levels
counts_per_substrate_long <- counts_per_substrate_long %>%
  mutate(Latin_Name = factor(Latin_Name, levels = latin_name_order))
# Create the plot with formatted title and y-axis label
ggplot(counts_per_substrate_long, aes(x = Substrate, y = Abundance, fill = Substrate)) +
  geom_bar(stat = "identity", position = "dodge") +
  geom_text(aes(label = round(Abundance, 1)), position = position_dodge(width = 0.9), vjust = -0.5, size
= 2.5) +
  facet_wrap(~ Latin_Name, ncol = 4, nrow = 5) +
  ylim(0, 5000) +
  labs(title = bquote("Species Count per 100m"^2~"of Substrate"),
       x = NULL,
       y = bquote("Count per 100m"^2)) +
  theme_minimal() +
  theme(axis.text.x = element_blank(),
        axis.ticks.x = element_blank(),
        strip.text = element_text(size = 8, face = "italic"),
        legend.position = "bottom",
        panel.grid.major = element_line(color = "grey80"),
        panel.grid.minor = element_line(color = "grey90")) +
 scale_fill_manual(values = substrate_colors,
                   labels = c("Cable", "Reef", "Sand", "Scour Protection"),
                    breaks = c("Cable", "Reef", "Sand", "Scour_protection"),
                    limits = c("Cable", "Reef", "Sand", "Scour_protection"))
```

```
# GGPLOT Loose sightings analysis

```{r Loose, warning=FALSE}
# Define the desired order for Latin_Name
latin_name_order <- c("Callionymus lyra",
                      "Mullus surmuletus",
                      "Pholis gunnellus",
                      "Gadus morhua",
```
```

````
                      "Pleuronectiformes platessa",
                      "Parablennius gattorugine",
                      "Trisopterus minutus",
                      "Myoxocephalus scorpius")

# Convert Latin_Name to a factor with specified levels
counts_per_substrate_long2 <- counts_per_substrate_long2 %>%
  mutate(Latin_Name = factor(Latin_Name, levels = latin_name_order))

# Create the plot with formatted title and y-axis label
ggplot(counts_per_substrate_long2, aes(x = Substrate, y = Abundance, fill = Substrate)) +
  geom_bar(stat = "identity", position = "dodge") +
  geom_text(aes(label = round(Abundance, 1)), position = position_dodge(width = 0.9), vjust = -0.5, size
= 2.5) +
  facet_wrap(~ Latin_Name, ncol = 4, nrow = 2) +
  ylim(0, 11) +
  labs(title = bquote("Species Count per 100m"^2~"of Substrate"),
       x = NULL,
       y = bquote("Count per 100m"^2)) +
  theme_minimal() +
  theme(axis.text.x = element_blank(),
        axis.ticks.x = element_blank(),
        strip.text = element_text(size = 8, face = "italic"),
        legend.position = "bottom",
        panel.grid.major = element_line(color = "grey80"),
        panel.grid.minor = element_line(color = "grey90")) +
  scale_fill_manual(values = substrate_colors,
                   labels = c("Cable", "Reef", "Sand", "Scour Protection"),
                    breaks = c("Cable", "Reef", "Sand", "Scour_protection"),
                    limits = c("Cable", "Reef", "Sand", "Scour_protection"))
```

# GGPLOT Method comparison

```{r compare, warning=FALSE}
# Define the desired order for Latin_Name
latin_name_order <- c("Callionymus lyra",
                      "Mullus surmuletus",
                      "Pholis gunnellus",
                      "Gadus morhua")
# compare both methods
comp_long <- comp_long %>%
  mutate(Latin_Name = factor(Latin_Name, levels = latin_name_order))


ggplot(comp_long, aes(x = Substrate, y = Abundance, fill = Substrate)) +
  geom_bar(stat = "identity", position = "dodge") +
  geom_text(aes(label = round(Abundance, 1)),
            position = position_dodge(width = 0.9),
            vjust = -0.5, size = 2.5) +
  facet_grid(Counting_methodology ~ Latin_Name) +
  ylim(0, 15) +
  labs(title = bquote("Species Count Comparison: CVAT Analysis vs. Video Tallying Analysis"),
       x = NULL,
       y = bquote("Count per 100m"^2)) +
  theme_minimal() +
  theme(axis.text.x = element_blank(),
        axis.ticks.x = element_blank(),
        strip.text = element_text(size = 8, face = "italic"),
        legend.position = "bottom",
        panel.grid.major = element_line(color = "grey80"),
        panel.grid.minor = element_line(color = "grey90")) +
  scale_fill_manual(values = substrate_colors,
                    labels = c("Cable", "Reef", "Sand", "Scour Protection"),
                    breaks = c("Cable", "Reef", "Sand", "Scour_protection"),
                    limits = c("Cable", "Reef", "Sand", "Scour_protection"))
````

```
View(counts_per_substrate)

str(counts_per_substrate)
summary(counts_per_substrate)
colnames(counts_per_substrate)[colnames(counts_per_substrate) == "Scour protection"] <- "Scour"
species_data <- counts_per_substrate[, c("Reef", "Scour", "Cable", "Sand")]
# Remove rows where all substrate values are zero
species_data_filtered <- species_data[rowSums(species_data) > 0, ]

summary(species_data_filtered)

nmds_result <- metaMDS(species_data_filtered, distance = "bray", trymax = 100)
plot(nmds_result, type = "t")

library(reshape2)
data_long <- melt(counts_per_substrate, id.vars = c("Common_Name", "Latin_Name"),
                  variable.name = "Substrate", value.name = "Abundance")

anova_result <- aov(Abundance ~ Substrate, data = data_long)
summary(anova_result)

# Extract residuals from ANOVA model
anova_residuals <- residuals(anova_result)

# Perform Shapiro-Wilk normality test on residuals
shapiro_test <- shapiro.test(anova_residuals)
print(shapiro_test)

# Q-Q plot to check for normality
qqnorm(anova_residuals)
qqline(anova_residuals, col = "red")

library(car)

# Levene's Test for homogeneity of variances
levene_test <- leveneTest(Abundance ~ Substrate, data = data_long)
print(levene_test)

###### TRYING TO MAKE THE DATA NORMAL.........
# Log transformation
# Assuming 'data_long' is your dataset
data_long$Log_Abundance <- log(data_long$Abundance + 1)

# Q-Q plot to check normality after log transformation
qqnorm(data_long$Log_Abundance)
qqline(data_long$Log_Abundance, col = "red")

# Shapiro-Wilk test to check for normality
shapiro.test(data_long$Log_Abundance)

library(MASS)
# Add a small constant (e.g., 1) to avoid zero values
data_long$Abundance_adj <- data_long$Abundance + 1

# Apply Box-Cox transformation
boxcox_res <- boxcox(lm(Abundance_adj ~ 1, data = data_long))

# Extract the optimal lambda
lambda <- boxcox_res$x[which.max(boxcox_res$y)]

# Perform the transformation using the optimal lambda
if (lambda == 0) {
  data_long$BoxCox_Abundance <- log(data_long$Abundance_adj)
} else {
  data_long$BoxCox_Abundance <- (data_long$Abundance_adj^lambda - 1) / lambda
}

# Check normality after Box-Cox transformation
```

```
qqnorm(data_long$BoxCox_Abundance)
qqline(data_long$BoxCox_Abundance, col = "red")
shapiro.test(data_long$BoxCox_Abundance)

data_long$Sqrt_Abundance <- sqrt(data_long$Abundance + 1)

# Check normality
qqnorm(data_long$Sqrt_Abundance)
qqline(data_long$Sqrt_Abundance, col = "red")
shapiro.test(data_long$Sqrt_Abundance)


boxplot(data_long$Abundance, main="Boxplot of Abundance", horizontal=TRUE)


#### NON PARAMETRIC> KRUSKAL WALLIS
# Gather the data into long format
counts_per_substrate_long <- counts_per_substrate %>%
  gather(key = "Substrate", value = "Abundance", Reef, Scour, Cable, Sand)

# Perform Kruskal-Wallis test
kruskal_test <- kruskal.test(Abundance ~ Substrate, data = counts_per_substrate_long)

# Print the result
print(kruskal_test)

# Install the necessary package for Dunn's test

library(FSA)

# Perform Dunn's test for pairwise comparisons
dunn_test <- dunnTest(Abundance ~ Substrate, data = counts_per_substrate_long, method = "bonferroni")

# Print the result
print(dunn_test)

# Check for and replace missing or zero values if necessary
counts_per_substrate <- counts_per_substrate %>%
  mutate_at(vars(Reef, Scour, Cable, Sand), ~replace(., is.na(.), 0))  # Replace NAs with 0 for now

# Get list of unique species
species_list <- unique(counts_per_substrate$Common_Name)

# Create an empty list to store results for each species
dunn_results <- list()

# Loop through each species to perform Dunn's test
for (species in species_list) {
  # Subset data for the species
  species_data <- subset(counts_per_substrate, Common_Name == species)

  # Reshape data to long format for the Dunn's test
  species_long <- species_data %>%
    gather(key = "Substrate", value = "Abundance", Reef, Scour, Cable, Sand)

  # Perform Dunn's test only if there is variation in the abundance (i.e., not all values are zero)
  if (sum(species_long$Abundance) > 0) {
    dunn_test <- dunnTest(Abundance ~ Substrate, data = species_long, method = "bonferroni")
    dunn_results[[species]] <- dunn_test$res  # Store results for the species
  }
}

# Combine all species results into one data frame
combined_results <- do.call(rbind, lapply(names(dunn_results), function(species) {
  result <- dunn_results[[species]]
  result$Species <- species  # Add species name to result
  return(result)
}))
```

```
# View the combined results
print(combined_results)

# repreat for counts_per_substrate2
```