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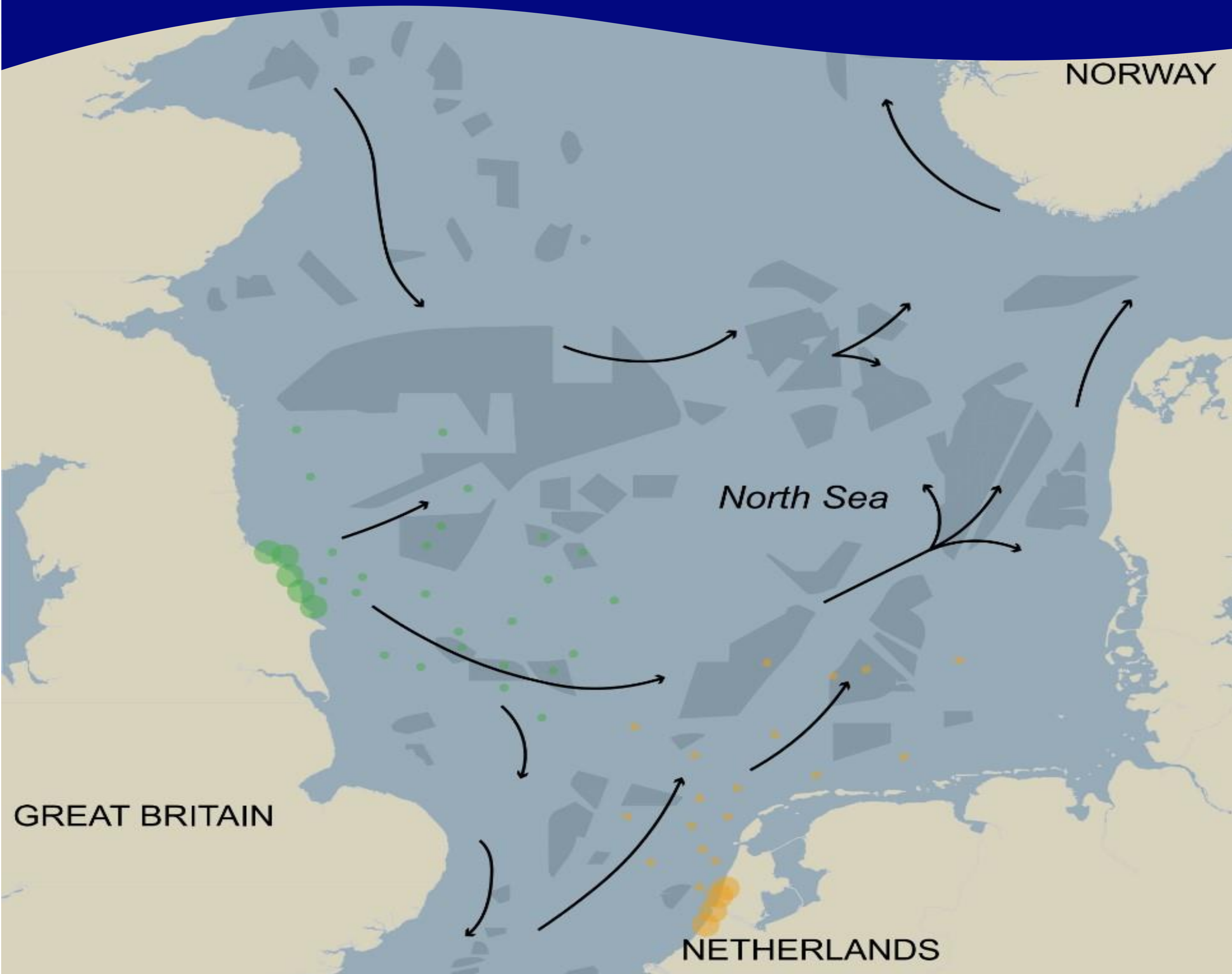
The potential of offshore wind farms to spread marine alien species

A Norwegian case study and review of current evidence



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Abstract

Alien species are organisms introduced to new areas through human activities that have been associated with artificial structures in coastal zones. Offshore wind farms (OWFs), rapidly expanding across marine environments, provide novel artificial surfaces that may facilitate the establishment and spread of alien species in regions lacking natural habitats. In the southern North Sea, offshore energy structures already support such species, with similar patterns observed globally. Despite international and national policies calling for better understanding of alien marine species, their pathways, and early detection systems, Norway lacks an understanding of how OWFs will impact the spread of alien marine species. The impact of OWFs on alien species spread remains understudied globally. This study synthesizes current knowledge and explores three mechanisms by which OWFs may promote alien species dispersal to Norway: (1) acting as stepping-stones for regional and international spread, (2) enabling hitchhiking on vessels and structures between offshore and inshore areas, and (3) creating refuges for alien species due to fishing restrictions within OWFs. We highlight relevant alien taxa for each and identify knowledge gaps, aiming to support biodiversity protection efforts and meet national and commercial obligations.

Keywords: Alien species, offshore wind, marine ecosystems, ecosystem services

Emneord: Fremmede arter, havvindanlegg, marine økosystemer, økosystemtjenester

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Summary

Alien species are organisms that spread into new areas where they do not naturally occur, aided by human activities, and are often associated with artificial structures in inshore areas. Their effects on native species and the functioning of marine ecosystems can be extensive, for example in altering habitat quality, restructuring food webs and transmitting disease and genetic material.

Offshore wind farm (OWF) developments are occurring rapidly and represent an increasing surface area of artificial structures. Scientific findings indicate this novel hard habitat could aid the establishment and spread of alien species in new areas otherwise lacking suitable habitat. Due to this, there is a need to assess the potential role that wind farm structures will play in spreading alien species through various mechanisms.

In the southern North Sea, offshore energy structures already act as habitats for alien species, and several other examples evidence this worldwide. Despite this, and the national and international policies requesting improved knowledge on alien marine species; new introduction pathways; and needs for early-detection systems, the effect of OWF activities on their spread remain understudied.

Here we performed a literature review to synthesise knowledge and assessed potential mechanisms of how OWFs may increase the spread of alien species to Norway, namely: 1) using OWFs as stepping-stones in dispersal between and throughout nations, 2) hitchhiking on vessels and OWF structures between offshore and inshore Norway and 3) alien species increasing in range and abundance as a result of refuge from fishing inside OWFs. For each, we collate observations of relevant alien taxa and identify opportunities to close knowledge gaps.

The literature suggests a) that OWF developments increase the likelihood of alien species spread to and throughout Norway in theory but that b) actions can be taken to mitigate this threat including monitoring and research as mechanisms to better understand the risk, and practices like vessel and structure cleaning to lower the potential for spreading We provide a roadmap as a guide for how to identify the risks associated with each mechanism of spread that may be required to facilitate national and commercial obligations for biodiversity protection. The roadmap is built around the following three pillars:

1. Monitor and research the presence and abundance of alien species on existing offshore structures
2. Predict broad-scale patterns of larvae dispersal from alien species hotspots and OWFs
3. Enhance communication and collaboration between stakeholders and policy makers to satisfy legislation at national levels

Sammendrag

Fremmede arter er organismer som sprer seg til nye områder hvor de ikke forekommer naturlig, ofte ved hjelp av menneskelig aktivitet og de er ofte knyttet til kunstige strukturer i kystnære områder. Deres påvirkning på stedegne arter og funksjonen til marine økosystemer kan være omfattende, for eksempel ved å endre habitatkvalitet, omstrukturere næringskjeder og spre sykdommer og genetisk materiale.

Utbygging av havvindanlegg skjer raskt og bidrar til en økt overflate av kunstige strukturer. Forskning viser at slike nye, harde habitat kan legge til rette for etablering og spredning av fremmede arter i områder som ellers mangler egnede habitater. Det er derfor behov for å vurdere hvilken rolle havvindstrukturer kan spille i spredningen av fremmede arter gjennom ulike mekanismer.

I den sørlige delen av Nordsjøen fungerer strukturer for offshore energi allerede som habitat for fremmede arter, og lignende eksempler finnes globalt. Til tross for nasjonale og internasjonale føringer om bedre kunnskap om fremmede marine arter, nye introduksjonsveier og behov for tidlig varsling, er effekten av havvindanlegg på spredningen fortsatt lite studert.

Vi har gjennomført en litteraturstudie for å sammenfatte kunnskap og vurdere sannsynlige mekanismer for hvordan havvindanlegg kan øke spredningen av fremmede arter til Norge, ved: 1) at de fungerer som spredningskorridorer mellom og innen nasjoner, 2) at arter "haiker" med fartøy og strukturer mellom offshore og kystnære områder i Norge, og 3) at fremmede arter drar nytte av fiskeforbud innenfor havvindanlegg. For hver mekanisme samlet vi observasjoner av relevante fremmede arter og identifiserte mulige løsninger for å tette kunnskapshull.

Litteraturen tyder på a) at utviklingen av havvind i teorien øker sannsynligheten for spredning av fremmede arter til og i hele Norge, men at b) tiltak kan iverksettes for å redusere denne trusselen, inkludert overvåking og forskning som mekanismer for å forstå risikoen bedre, og praksis som rengjøring av fartøy og strukturer for å redusere sannsynligheten for spredning. Vi presenterer et veikart som en veiledning for hvordan man kan identifisere risikoene knyttet til hver enkelt spredningsmekanisme som kan være nødvendig for å legge til rette for nasjonale og kommersielle forpliktelser for beskyttelse av biologisk mangfold. Veikartet er bygget opp rundt følgende tre pilarer:

1. Overvåke og forske på forekomsten og mengden av fremmede arter på eksisterende offshore-strukturer
2. Forutsi mønstre for larvespredning i stor skala fra hotspots for fremmede arter og havvindanlegg
3. Forbedre kommunikasjonen og samarbeidet mellom interessenter og beslutningstakere for å tilfredsstille lovgivningen på nasjonalt nivå

1 Introduction

Alien–or non-indigenous–species are universally recognised threats to coastal ecosystem resilience because of their capacity and demonstrated potential to alter habitat quality, restructure food webs and transmit disease and genetic material (Glasby et al. 2007; Adams et al. 2014; Bishop et al. 2017). Despite success in controlling ship ballast spread of alien species through the Ballast Water Management Convention in 2017, several vectors of alien species continue to cause concern in the Northeast Atlantic; including the provision of new artificial habitat by offshore wind farm (OWF) developments (Adams et al. 2014; Rumes and Kerckhof 2021; Ben Rais Lasram et al. 2019), that are occurring at rapid pace to meet climate and energy targets. Inshore, artificial structures (pontoons, harbour walls, pilings) are well documented to provide open niches for fouling alien species, enhancing their establishment (Glasby et al. 2007; Bishop et al. 2017). Despite limited investigations offshore, several cases indeed show that alien species foul or shelter on or around oil, gas, wind structures (platform jackets, turbine columns, foundations, anchors, scour protection, chains, and cables) (Coolen et al. 2020a; De Mesel et al. 2015), and unknowns exist for how the scale-up of offshore wind will expand their spawning ranges and exacerbate their spread. The lack of this information causes problems in being able to predict and manage risk and contradicts Target 6 of the Kunming–Montreal Global Biodiversity Framework to reduce the introduction and impact of invasive alien species by at least 50 % by 2030.

Some countries (e.g., UK) include alien species management plans (Payne, Cook, and Macleod 2014) in environmental impact assessments for offshore wind farms (RPS 2022). Norway lacks a formal plan for alien species but states in its ‘Ocean Management Plan’ (Meld. St. (2023-2024); www.regjeringen.no) that there is ‘a need for more systematic monitoring of the spread and impact on native species and habitats’, with a focus on ‘introduction pathways’. In particular, the Norwegian government wants to increase knowledge about and monitor the occurrence, spread, and effects of invasive species in Norwegian marine areas, and understand how changed traffic patterns for shipping will alter the risk of spreading invasive species. As an objective there is specific mention to monitor inshore habitats for alien species presence. However, offshore habitats may also be important, as we will assess here, given that the effects of offshore wind can be wide reaching and impact ecosystem services throughout Norway's Exclusive Economic Zone (EEZ) and internationally (Cochrane et al. 2024).

Additional European and international legal obligations exist to report on invasive species like the Invasive Alien Species Regulation (EU 1143/2014) i.e. measures to prevent, minimize, and mitigate the adverse impacts of alien species on native biodiversity and ecosystem services (Lehtiniemi et al. 2015). Given the North Sea Summit goal of 120 GW of installed Offshore Wind Farm (OWF) capacity in the North Sea, and Norway's goal of allocation areas with a potential for 30 GW production by 2040, there is an urgent need to understand if offshore wind structures may increase alien species spread to and throughout Norway, and place its habitats, industries and human health at greater risk to alien species.

Norway’s relative geographic isolation and cold climate has resulted in just 47 marine alien species being recorded (mostly in the south and mid-west (Husa et al. 2022). However, the rate of observations has increased during the past two decades with increased monitoring effort (Husa et al. 2022) and Norwegian habitat suitability is predicted to increase for alien species with ocean warming (Seebens et al. 2016). In the Northeast Atlantic, the primary invasion of alien species–e.g. from Asia or the Western Atlantic–has typically been to southern North Sea countries where their secondary invasion–or dispersal–subsequently spread macroalgae and invertebrates like the Pacific oyster (*Crassostrea gigas*), the sea squirt (ascidian) *Didemnum vexillum*, and the algae *Codium fragile* to Norwegian coasts.

Here, we highlight three mechanisms by how the up-scaling of offshore wind may theoretically increase invasive species risks in Norway, identify which are relevant alien groups (taxa), and define research gaps to be explored to better understand and manage invasive species risk.

2 Methods

This report is based on a literature review where we first assessed relevant mechanisms of alien species dispersal using several studies (Adams et al. 2014; De Mesel et al. 2015; Rumes, and Kerckhof. 2021; Dauvin 2024). We then collated records of alien species found on offshore energy structures, focusing on those established in the North and Norwegian seas. We gathered functional data for the species from World Register for Marine Species (WoRMS; (https://www.marinespecies.org, 2024) including a taxa pelagic larval phase duration, tolerance for high exposure offshore, their reproductive frequency and clonality. We estimated the overall likelihood of each species expanding range using offshore structures and dispersal assuming that long larval duration, high offshore tolerance, frequent spawning and clonal spawning strategies result in the highest likelihood.

To identify the most relevant taxa typically associated with ship hulls–and therefore offshore structures following similar movement patterns in and out of harbours–we filtered marine records collated in the World Register of Introduced Marine Species (WRiMS: https://www.marinespecies.org/introduced, accessed 16.10.2024). Such filtering removed records not identified to species or family level, not associated with ship hulls and listed as non-invasive. We provided relevant functional traits for the 10 most common taxa that may be useful in predicting the likelihood of transport from harbours. This functional data was from WoRMS (https://www.marinespecies.org, 2024) on their reproductive seasons and an overall likelihood of transport from harbours assuming presence and that OWF structures will be assembled in ports for periods of up to a few weeks.

Relevant species for the scenario of OWFs as refuges for mobile fauna from fishing were taken directly from the literature as well-known Norwegian case studies.

3 Mechanisms of alien species spread

3.1 Increased dispersal of offspring aided by the colonisation of offshore stepping-stone habitats

The scale-up of offshore wind represents tremendous surface-area increases in hard-bottom habitats in areas mostly comprising soft-bottom habitats. Offshore wind structures are, in theory, 'stepping-stones' (Adams et al. 2014) where benthic species–including alien species–may disperse to, establish, spawn and disperse between (Degraer et al. 2020; De Mesel et al. 2015); expanding their range of dispersal–or increasing number of offspring (propagule pressure), to new areas **(Figure 1).**

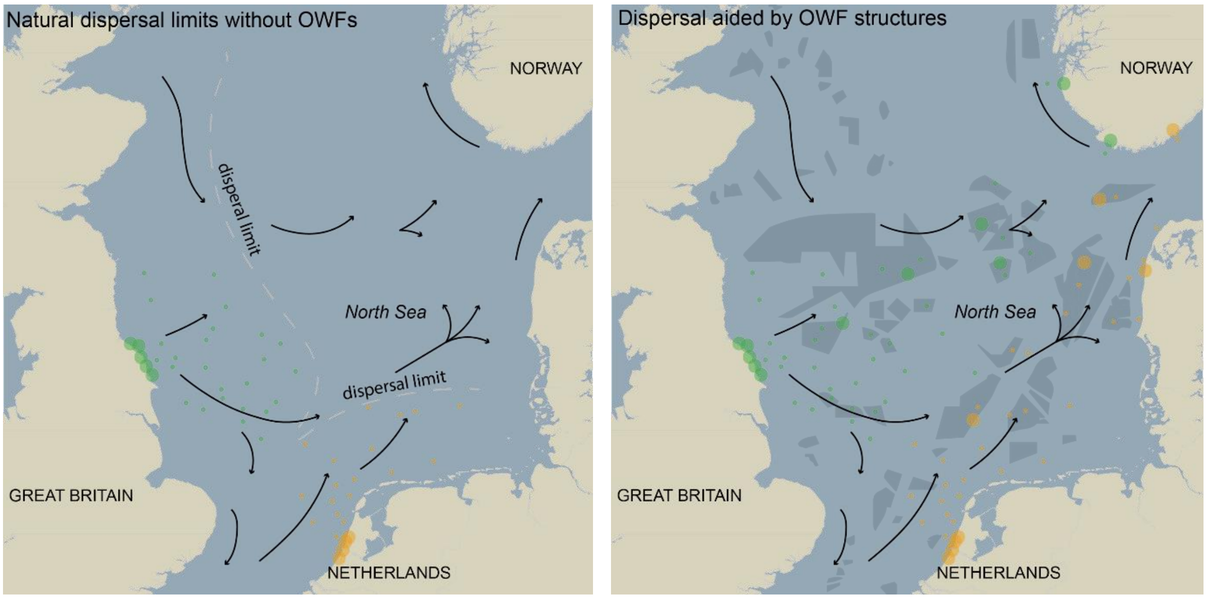

***Figure 1**. Schematic representation of stepping-stone theory for offshore wind farms (proposed OWFs, dark polygons) in the North Sea showing (left) theoretical original dispersal limit of alien species (green and orange circles) from coasts depending upon pelagic larval phases and currents (black arrows). On the right we depict a theoretical new extent for alien species under OWF scenarios.*

Given that the North Sea is shallow, comprising mixed-substrate with many artificial structures on its seabed, including pipelines and shipwrecks; opportunities for the settlement and shelter of benthic–including alien–species will predominantly increase for intertidal and shallow-subtidal dwelling species (Degraer et al. 2020; De Mesel et al. 2015). This has been exemplified in the southern North Sea where the greatest diversity of alien species were found in the intertidal parts of offshore wind structures (De Mesel et al. 2015); species like the barnacle (*Megabalanus coccopoma*), amphipod (*Jassa marmorata*), pacific oyster (*Crassostrea gigas*) and crab (*Hemigrapsus sanguineus*) (De Mesel et al. 2015). Indeed, the diversity of marine alien species in European waters is greater in the upper 40 m, largely as a result of most invasion vectors being forms of aquaculture and shipping (Costello et al. 2022; Vinagre et al. 2020).

Key factors that will dictate which alien species may establish offshore under dispersal scenarios are 1) pelagic larvae or juvenile phase duration i.e., long enough to allow for dispersal to offshore wind structures and subsequently to coasts, and 2) tolerance of high exposure i.e., able to foul, survive and release propagules. A range of ecological and biological variables will influence how likely species are to reach certain areas, including their reproductive modes e.g., sexual or asexual. Furthermore, a range of variables will influence how likely species are to establish according to their competition with native fouling organisms (Airoldi et al. 2015), including the substrates, species and environmental conditions present.

Pelagic larvae phases of benthic marine organisms vary in duration as a result of different life history strategies. In this context, relevant groups are planktotrophic larvae (those that feed on plankton) like the Pacific oyster (*Crassostrea gigas*), that typically have a larval duration ranging from two weeks to several months or Lecithotrophic larvae (those that rely on yolk reserves and do not feed) like the leathery sea squirt (*Styela clava*), with larval phases from a few days to two weeks. In addition, mobile species like Japanese skeleton shrimp (*Caprella mutica*) are theoretically dispersed to offshore structures as juveniles in storms (Coolen et al. 2018), given that adults carry eggs. Currents and surface wind (Demmer et al. 2022) will dictate where benthic organisms spread to, and larval phase duration will dictate the dispersal limit **(Figure 1)** along any given route. For the pacific oyster, this can be ca. 100 km (Rinde et al. 2017) while sea squirts or sponges may disperse over shorter distances (Álvarez-Noriega et al. 2020). Studies on native fauna suggest that in the North Sea, dispersal durations of more than several weeks lead to wide dispersal (ca. >100 km) and population homogenisation (Coolen et al. 2020a; Pechenik 1999), as well as offshore oil and gas structures comprising closely connected habitats (Mayorga-Adame et al. 2022). Meanwhile, offshore wind structures more than 85 km from the coast are considered isolated (Coolen et al. 2020b).

Despite the many forms of existing artificial surface structures like offshore wind, buoys and oil and gas structures, there are limited observations of alien species establishing offshore worldwide due to a lack of monitoring requirements rather than lack of research interest (Fortune et al. 2024). While international cases were not a focus here, the species are relevant in acknowledging the potential for Norway like the sea squirt *Didemnum vexillum* fouling Block Island Wind Farm in the USA (Guarinello and Carey 2020). For those records of alien species established in the North and Norwegian seas on offshore energy structures **(Table 1)**, all originate from the southern North Sea. The scarcity of publicly available data for the central and northern North Sea and Norwegian waters, does not suggest the low potential for spread in Norway, simply more effort in alien species observations on artificial energy structures Belgian and Dutch waters. So far, around 3 % of the known alien species in European waters have been reported at OWFs (Dauvin et al., 2024), most likely due to the limited number of observations, quantitative data and relatively recent development of the offshore wind industry. Studies that exist for the northern and central North Sea have been limited due to surveys performed without focus on alien species using only cameras, which limit the ability to observe alien species (Whomersley and Picken 2003; Karlsen et al. 2022).

***Table 1**. Collation of alien species records of observations on offshore energy structures in the North and Norwegian Seas with functional data (from WoRMS: https://www.marinespecies.org, 2024)*

Taxa	Species	Pelagic larval duration	Offshore tolerance	Frequency of Spawning	Clonal Species	Likelihood of expanding range using offshore structures	Observation
Barnacles	*Amphibalanus improvisus*	2-5 weeks	High	1-2 broods per year	No	High	Netherlands (Coolen, et al. 2020b)
	Austrominius modestus	10-40 days	High	Multiple broods per year	No	High	Netherlands (Coolen, et al. 2020b)
	Perforatus perforatus	2-4 weeks	High	Multiple broods per year	No	High	Belgium (De Mesel et al. 2015)
	Austrominius modestus	10-40 days	High	Multiple broods per year	No	High	Belgium (De Mesel et al. 2015)
	Megabalanus coccopoma	3 weeks	High	Multiple broods per year	No	High	Netherlands (Coolen, et al. 2020b) Belgium (De Mesel et al. 2015)
Crabs	*Hemigrapsus sanguineus*	16-25 days	High	Multiple broods per year	No	High	Belgium (De Mesel et al. 2015)
Bivalves	*Crassostrea gigas*	2-4 weeks	High	Multiple broods per year	No	High	Belgium (De Mesel et al. 2015)

Tunicates	*Didemnum vexillum*	Short-lived larvae	High	Multiple broods per year	Yes	High	Netherlands (Coolen, et al. 2020b)
Bryozoans	*Fenestrulina delicia*	Short-lived larvae	Moderate	Multiple broods per year	Yes	Moderate	Netherlands (Coolen, et al. 2020b)
	Smittoidea prolifica	Short-lived larvae	Moderate	Multiple broods per year	Yes	Moderate	Netherlands (Coolen, et al. 2020b)
Sea Anemones	*Diadumene lineata*	Short-lived larvae	Moderate	Multiple broods per year	Yes	Moderate	Netherlands (Coolen, et al. 2020b)
Tunicates	*Diplosoma listerianum*	Short-lived larvae	Moderate	Multiple broods per year	Yes	Moderate	Netherlands (Coolen, et al. 2020b)
Limpet	*Crepidula fornicata*	4-5 weeks	Moderate	Multiple broods per year	No	Moderate	Netherlands (Coolen, et al. 2020b)
Amphipods	*Caprella mutica*	No pelagic phase	Moderate	Multiple broods per year	No	Low	Netherlands (Coolen, et al. 2020b)
	Jassa marmorata	No pelagic phase	Moderate	Year-round, with peaks in spring and winter	No	Low	Netherlands (Coolen, et al. 2020b)
	Monocorophium sextonae	No pelagic phase	Moderate	Year-round	No	Low	Netherlands (Coolen, et al. 2020b)
Insects	*Telmatogeton japonicus*	No pelagic phase	Low	Multiple broods per year	No	Low	Netherlands (Coolen, et al. 2020b) Belgium (De Mesel et al. 2015)

Several of the species observed on offshore energy structures are indeed better established in southern North Sea coasts than in Norway, with sufficient larval duration (ca. 14-21 days) and moderate or high likelihood of tolerating exposed conditions (Katsanevakis et al. 2023), and correspondingly a moderate or high likelihood of benefitting from OWFs as stepping stones. These include the pacific oyster, American slipper limpet (*Crepidula fornicata*) and the Japanese sea squirt (*Didemnum vexillum)* and are listed as high risk in Norway (https://www.artsdatabanken.no/fremmedearter) suggesting that there may be greater impacts of alien species on native fauna under the upscaling of OWFs for alien species that demands monitoring and management to project to Norwegian habitats.

Despite limited information on alien marine parasites and pathogens due to a lack of study (Piarulli et al. 2024), we would be remiss not to highlight that micro-organisms are dispersed alongside their macro-organism hosts (Foster et al. 2021) including as larvae and have been shown to survive outside the host for periods of weeks to months (Georgiades et al. 2021; Goedknegt et al. 2016). Consequently, and similar to macro-organisms, the spread of alien or pathogenic micro-organisms may be facilitated by offshore structures, as evidenced by examples of alien pathogens *Marteilia refringens* and *Perkinsus olseni* infecting bivalves fouling offshore energy structures in Asia (Yan et al. 2006). Disease is one of the biggest threats to native species, aquaculture and human health (Jennings et al. 2016) and we highlight that research is urgently needed on its spread and impact related to offshore wind development.

This process suggests that 1) the spread of marine alien species represents a greater challenge than currently recognised given the diversity provided by just two studies, that 2) the range expansion of species by offshore structures has already began in the southern North Sea, 3) increased study effort is likely to reveal characteristics of alien species observed in larval duration and offshore tolerance (Table 1).

3.2 Inshore-offshore transport during installation, maintenance and decommissioning

In addition to the dispersal of alien species by currents, to and from OWFs, opportunities exist for 'hitchhiking' offshore and inshore to ports on vessels and foundations during the installation, maintenance and decommissioning of OWFs. As shown in the decommissioning of oil and gas platforms, the slow movement of offshore structures and the lack of guidelines or regulations on their cleaning often results in the translocation of ecological communities fouling them (Page et al. 2006; Pajuelo et al. 2016). This can in theory transport fouling alien species established around harbours to OWFs (ICES 2025), where they could spread further, and conversely vessel and structure movement could transport species established in OWFs, inshore **(Figure 2).**

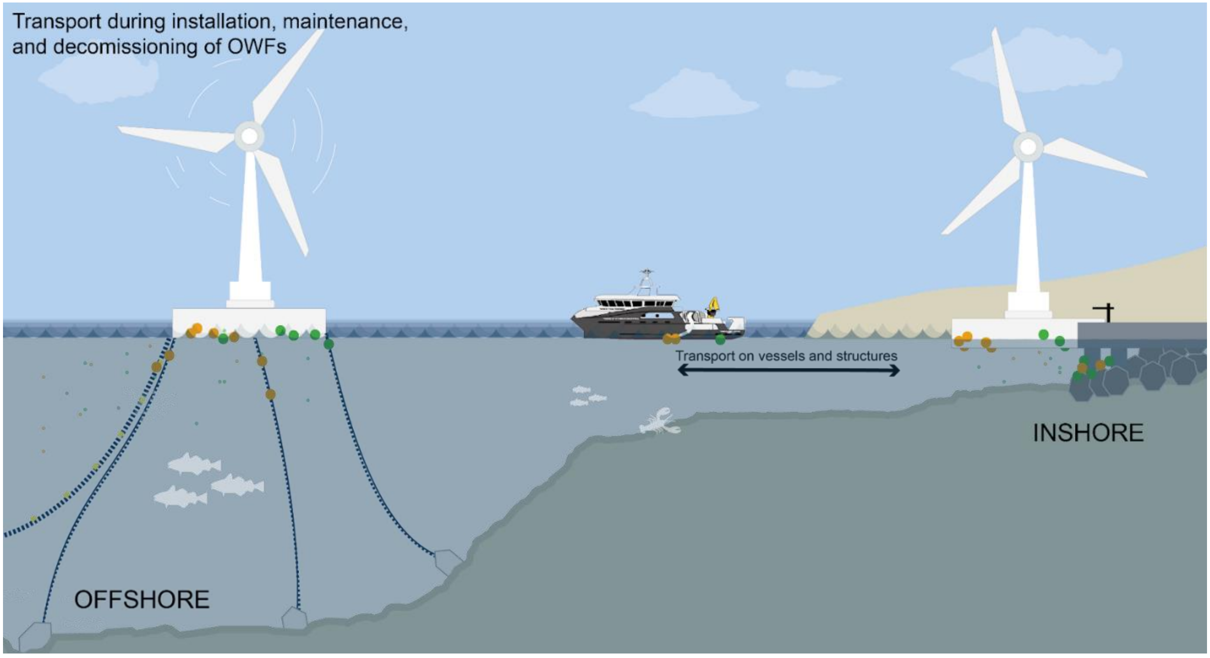

Figure 2*. Schematic representation of the direct transport of alien species (green and orange circles) offshore and inshore to ports on vessel hulls and offshore wind structures during installation, maintenance and decommissioning of offshore wind farms (OWFs).*

Despite alien species risk around ports or harbours being recognised as high in Norway (Husa et al. 2022) the role of vessels (and artificial surfaces) as vectors of alien species spread is vastly underappreciated due to a lack of survey effort (Piarulli et al. 2024; Costello et al. 2022). Current international attempts to define and enforce effective international and national ship cleaning regulations (e.g. MEPC.378(80)) exemplify the risk of shipping and knowledge should be gathered to assess relevant mitigation for offshore artificial structures like OWFs, Oil and Gas platforms (O&G) and buoys.

In contrast to dispersal-only strategies **(Figure 1)**, the transport of alien species to and from OWFs by vessels or structures **(Figure 2)** may include those with very short larval duration phases that have fouled structures inshore; as theorised for the Bryozoan *Watersipora* sp. observed on OWF structures off the coast of USA, which is only pelagic for 24 hours (Viola et al. 2018).

Relevant taxa for transport by structures and ship surfaces **(Table 2)**, as summarised by taking the 10 most common taxa from WRiMS, we find several overlaps with species recorded at OWFs in the southern North Sea in 6 groups (Gymnolaemata, Thecostraca, Bivalvia, Gastropoda, Hydrozoa, and Malacostraca). Several of these have moderate or high likelihoods of transport to/from harbours **(Table 2**) if present.

The relevance of this list is quite high given that cleaning regulations, like those under discussion for ship hulls, would need to be established and conducted with greater frequency than several weeks to lower these likelihoods. Indeed, if OWF structures are present inshore during assembly for a period of days up to a few weeks and not cleaned, there appears to be risks of transporting alien marine species if they are present in that given inshore area. In theory, each of the taxa could also establish offshore at different time points and be translocated inshore during maintenance or decommissioning, given that there are no cleaning regulations. It is important to mention that micro-organisms are sparsely represented (1/10 taxa) due to a lack of study effort (Piarulli et al. 2024). Despite being frequently associated with biofouling, marine invasive pathogens remain poorly understood (Georgiades et al. 2021). It is however likely that the movement of vessels (including offshore structures) facilitate their dispersal where survival outside the host is limited in duration (Foster et al. 2021; Georgiades et al. 2021). In addition to the dispersal of alien species by currents, to and from OWFs, opportunities exist for 'hitchhiking' offshore and inshore on vessels and foundations during the installation, maintenance and decommissioning of OWFs.

Table 2. *Ten most common taxa containing internationally reported alien marine species associated with ship hulls (WRiMS: https://www.marinespecies.org/introduced, 2024), with indications (from WoRMS: https://www.marinespecies.org, 2024) on their ecology.*

Taxa	Order	Time to Establishment on a Surface	Primary Succession Phase	Seasons Where Fouling is Most Likely	Likelihood of Transport to/from Harbours if Present
Marine bryozoans	Gymnolaemata	2-10 hours for initial settlement	Pioneer	Year-round, with peaks in summer and autumn	High
Copepods	Copepoda	Rapid colonization; within days	Pioneer/Intermediate	Year-round, with peaks in summer and autumn	High
Marine microalgae diatoms	Bacillariophyceae	Rapid colonization; within days	Pioneer	Spring and summer	High
Barnacles	Thecostraca	1-2 weeks for initial settlement	Pioneer	Summer and autumn	High
Bristle worms	Polychaeta	1 to 2 months	Pioneer/Intermediate	Spring and summer	Moderate

Clams, oysters, mussels	Bivalvia	1-3 months	Pioneer	Spring and summer	Moderate
Snails, slugs, limpets	Gastropoda	Varies; some species can foul within weeks	Pioneer/Intermediate	Year-round, with peaks in warmer months	Moderate
Corals, sea firs, jellyfish	Hydrozoa	Varies from days to weeks	Pioneer	Summer and autumn	Moderate
Crabs, lobsters, shrimps	Malacostraca	Varies widely; generally several months	Intermediate/Climax	Year-round, with peaks in warmer months	Low
Tubular foraminiferans	Tubothalamea	Varies; generally several weeks	Intermediate/Climax	Year-round, with peaks in warmer months	Low

The likelihood of translocation from shore depends on how quickly a species can colonise a new structure, i.e., what primary succession phase does it require and how regularly it reproduces. It is important to recognise that some reproductive seasons carry additional risks that should be considered during the transport of vessels and structures.

This process highlights that despite potential hull cleaning regulations, there will remain opportunities for alien marine species to be translocated from inshore areas to OWFs where they could establish and spread further, and that mitigation strategies for cleaning vessels and structures will depend on season and species e.g., the Japanese sea squirt is a clonal organism that is recommended not be disturbed during summer months when asexually active https://bim.ie/invasivespecies/seasquirts/.

3.3 Offshore wind farms as refuges from fishing, limiting the management of mobile alien species

In the Barents Sea, fishing plays a crucial role in controlling the westward range expansion of the invasive red king crab (*Paralithodes camtschaticus*) from Russia. The Norwegian government has implemented regulations to manage king crab: West of 26°E, it is fished unrestrictedly, while East of 26°E, fishing is regulated in line with its abundance (https://hi.no/en/hi/temasider/species/red-king-crab). In theory, OWFs may constitute refuges for marine fauna from fishing due to safety zone restrictions where fisheries cannot operate **(Figure 3)**. Excluding fisheries in OWF areas is a well-studied phenomenon that typically results in an increase in the diversity and abundance of marine fauna over time (Ashley, Mangi, and Rodwell 2014). As yet, it is unknown to what extent fisheries and OWFs will overlap in Norway because the extent of safety zones requires definition for each site (Offshore Norge 2023). For the existing floating facility at Hywind Tampen, fisheries typically do not operate within a 500 m limit but several passive fishing gears (e.g. pots, gill-nets, long-lines) have been tested within this limit to assess possibilities (Offshore

Norge 2023). Fishing may therefore be a potential solution to hinder the spread of some alien species, e.g. red king crab, if their distribution coincides with OWFs, as **Figure 3** depicts.

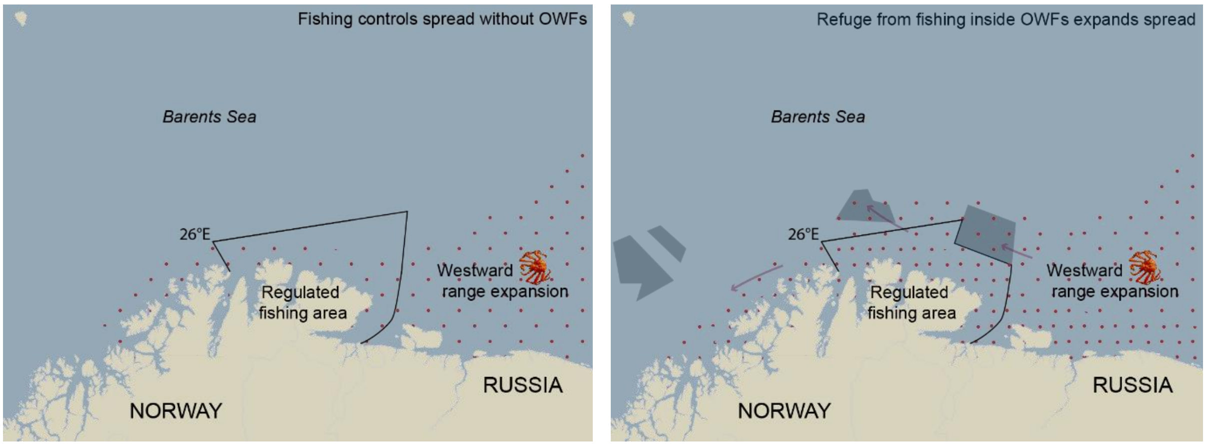

Figure 3. *Schematic depicting existing distribution (IMR, Norway) and theoretical expansion (red arrows) of the invasive red king crab (red dots depict distribution extent) if the development of offshore wind farms (OWFs, dark polygons) limits fisheries management of the species.*

However, if fisheries cannot or do not operate in OWFs where alien species e.g. red king crab may reside, their management may need to adapt to avoid an increase in abundance and spread. The same theory applies to multiple mobile alien species, but we recognise research is required to assess their likelihood and potential solutions. It must be noted that at present, red king crab fishing occurs coastally and in fjords. Its fisheries do not overlap with the NVE identified areas but the red king crab is expected to increase its range in the Barents Sea (Falk-Petersen et al. 2011), hence overlapping with Nordavind A and B. Other species like snow crab (*Chionoecetes opilio*) may similarly increase their abundance and or distribution through the same mechanism, although its fishery is further north in the Barents Sea and its distribution is not overlapping planned OWFs to a great degree https://www.hi.no/en/hi/temasider/species/snow-crab-chionoecetes-opilio. Snow crab is, however, expected to expand its distribution further in the western Barents Sea following climate change (Lorentzen et al. 2018).

Complicating the issue, the reef effects of offshore wind structures may result in comparatively favourable habitats for red king or snow crabs due to the likely fouling and sheltering of a host of benthic invertebrates – periodically falling to the seafloor and supplementing prey opportunities (Ivanov et al. 2021). However, given that the red king crab is reliant on inshore spawning migrations (Falk-Petersen et al. 2011), increased survival rates within OWF areas could in theory be compensated against by increased fishing effort on the perimeter of OWFs, and this could be explored as a management measure. The same would not be the case for the snow crab that spawns offshore (Hjelset et al. 2021).

The literature suggests that the coexistence of fisheries and OWF could be considered and studied to evaluate its potential to control the spread of alien and invasive species. However, useful first avenues involve modelling alien species spread under climate change and management scenarios, including relevant commercial mobile macro fauna like red king crabs, to evaluate the risk of range expansion into OWF farm areas and the ecological suitability of these habitats under OWF-modified scenarios.

4 Discussion

In our literature review, we found published support for three potential mechanisms of alien species spread that could be relevant for Norway in its offshore wind developments. These are:

- Increased dispersal of offspring aided by the colonisation of offshore stepping-stone habitats
- Inshore-offshore transport during installation, maintenance and decommissioning
- Offshore wind farms as refuges from fishing, limiting the management of mobile alien species

We summarize and discuss the importance of these findings for reducing the alien species risk of Norwegian offshore wind development to Norwegian marine ecosystems. We also summarize potential mitigation measures based on findings from the literature review, the gaps in knowledge that should be filled through research, and a roadmap to achieve this.

4.1 Can we minimize risks based on knowledge from inshore waters?

Mitigation measures informed by inshore cases include suitable location choice to prefer hard substrate areas over soft substrate areas and therefore to avoid a soft-to-hard habitat change as much as possible. In Norway, inshore offshore wind activities have been limited i.e. due to risks to seabird mortality. Hence, Norwegian offshore wind activities will take place further offshore where we mostly have soft-bottom areas, which makes this a less relevant mitigation measure. Moreover, this measure is not as relevant to alien marine species considering that most inhabit shallow subtidal and intertidal areas.

Material choice may be explored to limit the settlement of fouling alien species, including antifouling materials especially related to how quickly alien species may colonise structures because this would inform risks (Farr et al. 2021). Thirdly, transport should be considered for how vessels servicing the farm may transmit fauna and flora to the farm from other areas given these routes could be reduced or altered (Adams et al. 2014).

For example, measures could be taken to avoid contact with areas known to contain invasive species of risk and/or the cleaning of vessels prior to their arrival at farms (Costello et al. 2022). Likewise, if invasive species become established at offshore wind farms, their transport to other areas can be reduced by careful planning with vessel movement and cleaning prior to the transport of turbines and structures to harbours for maintenance (Adams et al. 2014). This could follow similar guidelines being developed by the International Maritime Organisation for ship hulls (MEPC.378(80)). Importantly, the establishment of native fauna and flora on structures may be important in both limiting available space for some alien species or creating habitat complexity and sheltering others (Airoldi et al. 2015). Although there may be ecological costs to minimising or maximising area cover of native fauna, research is required of how this trade-off functions in offshore areas, and especially in deeper waters, since this argument is often made for shallow coastal infrastructure (Adams et al. 2014; Airoldi et al. 2015).

4.2 Gaps in knowledge and roadmap to identify risk

We highlighted three potential theories that may increase the risks of marine alien species and pathogen spread and impact and identified some relevant taxa for each theory. Given international concern for this issue (Airoldi et al. 2015; Adams et al. 2014; Rumes and Kerckhof 2021; Ben Rais Lasram et al. 2019; ICES 2025), threats to marine industries like aquaculture, human health (Jennings et al. 2016) , and that each

EU country is legally obliged to monitor alien species through the EU Marine Strategy Framework Directive among others (Lehtiniemi et al. 2015), proper assessments and validation are required to predict and minimise the risks. Building on useful suggestions from the southern North Sea (Rumes and Kerckhof 2021); we highlight the following objectives as priorities to advancing understanding of risks:

1. **Monitor and research the presence and abundance of alien species on existing offshore structures and offshore wind related inshore ports**
   - Develop technical, standardised and cost-effective solutions for the detection and/or removal of intertidal and subtidal alien species, including their associated micro-organisms
   - Identify areas or characteristics of artificial substrates correlated with alien species presence
   - Understand fouling rates and ecological succession for vessels/structures moored inshore and develop guidelines for the assembly of offshore structures

2. **Predict broad-scale patterns of larvae dispersal from alien species hotspots and OWFs**
   - Quantify the influence of OWFs on changes in currents, oceanographic features and the survivability of larvae
   - Model alien species establishment offshore and changes in their distribution
   - Model effects of environmental conditions (Seebens et al. 2016) to assess risks under climate change scenarios and develop trait-based species lists and their associated risk to better target monitoring efforts.

3. **Enhance communication and collaboration between stakeholders and policy makers to satisfy legislation at national levels**
   - Standardise monitoring protocols (Fortune et al. 2024), set up a national monitoring programme (Husa et al. 2022; Borgersen et al. 2022) and coordinate reporting with other relevant marine stakeholders including the co-development of guidelines for vessels via MEPC.378(80)
   - Assess the consequences to fishing of OWFs ability to refuge and spread invasive species
   - Assess potential and methods to promote native species as buffers (Chan and Briski 2017) against establishment of alien species

4.3 The need for monitoring as a first priority

It should be recognised that the issue of marine alien species fouling offshore structures is not a new one. While we theorise that new OWFs may increase the risk of spreading alien species in the future it is certainly the case that offshore and inshore artificial structures have been established for decades in the North Sea and off Norway. Therefore, increasing the connectivity of alien species between the North Sea countries via offshore structures has long begun. Existing structures may help to shed light on immediate actual risks facing native Norwegian habitats. Given that early-indication and action is a more economically attractive option to reduce ecological consequences than dealing with an invasion after establishment, their monitoring should be considered a priority. It may also be the case that existing offshore structures may act as earlier indicators of alien species soon able to reach the coasts; a greater degree of certainty on which species may arrive and where to focus efforts may reduce the risks of establishment. The need for early indicators are exemplified by the key goal of Miljødirektoratet (Monitoring of Alien Marine Species - miljødirektoratet.no) to ‘detect new establishments at an early stage, and if possible, to implement measures to prevent further establishment and spread’. Therefore, we recommend alien species be considered in plans for a formal monitoring programme for offshore wind in Norway.

While there are challenges to this first step in terms of developing cost-effective monitoring techniques, there are a host of methods available including ROV visual camera surveys *in situ* (providing their survey effort is sufficient), morphological identifications of surface scrapes or structures in dry docks, and eDNA qPCR assays or metabarcoding (Knudsen et al. 2022), that can be adapted for context (Ekrem et al. 2023) and are important in monitoring micro-organisms but that need to be optimised for offshore use due to dynamic conditions and low DNA shedding rates of invertebrates. There are suggestions for national monitoring programs for alien marine species that can be built upon and expanded to offshore cases (Husa et al. 2022; Borgersen et al. 2022).

5 Conclusion

The risk of alien species spreading to Norwegian habitats seems likely to increase under the roll-out of large offshore wind developments across the North and Norwegian Seas. However, the degree of risk is largely uncertain due to a lack of study. We identify several robust ways to begin to understand and manage this risk and suggest support for these types of studies given the ecological change and impact to society that additional or increased alien species may bring. We highlight the national and international policy that exemplifies the need for this.

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