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► **To cite this version:**

Jean-Claude Dauvin. Do offshore wind farms promote the expansion and proliferation of non-indigenous invertebrate species?. *Marine Pollution Bulletin*, 2024, 206, pp.116802. 10.1016/j.marpolbul.2024.116802 . hal-04670533

HAL Id: hal-04670533

<https://normandie-univ.hal.science/hal-04670533v1>

Submitted on 12 Aug 2024

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Do offshore wind farms promote the expansion and proliferation of non-indigenous invertebrate species?

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ARTICLE INFO

Keywords:

Non-indigenous species
Reef effect
Dispersion
Offshore wind farm

ABSTRACT

Based on a search of publications in the scientific literature as well as international reports available online, I draw up a list of 25 documents which include cross-references to the terms offshore wind farms (OFW), and non-indigenous species (NIS). This review shows that no relationship has yet been clearly established between the implementation of OFWs and the colonization of NIS on turbine foundations and scour protections. Evidence for such an effect needs to be documented and confirmed in the future.

1. Introduction

In the current debate on the implementation of offshore wind farms in the European coastal marine zones of the North-East Atlantic and Mediterranean Sea, one of the major assumed effects is the role these parks might play in the spread of non-indigenous species (NIS), some of which are potentially invasive. But we do not even know what observations this assumption is based on. Do wind farm infrastructures behave differently from other artificial structures built offshore, including the foundations and scour protections of offshore wind turbine piles? We also need to know which species are involved.

At present, the implementation of numerous Offshore Wind Farms (OFW) has led to many studies on the effects of such offshore infrastructures on the functioning of marine ecosystems mainly in three marine coastal zones (Degraer et al., 2020; Hutchison et al., 2020). These include the North-east European zone mainly in the south of the North Sea and around the United Kingdom (Degraer et al., 2020), but also along the north-eastern coast of North America (Hutchison et al., 2020) and along the coast of China (Chen et al., 2023). It is often stressed that the reef effect is the most important impact affecting the four types of wind turbine structure: monopiles, gravity-based foundations, jacket and tripod structures (Raoux et al., 2017, 2019; Degraer et al., 2020). The major difference between wind infrastructures and artificial reefs (AR) submerged on the sea bottom is the presence of an intertidal zone on the foundations of wind turbines and a bathymetric zonation of the flora and fauna that have colonized these surfaces from their aerial part to the seabed. Moreover, in OFW structures there is the presence of an intertidal splash zone in the offshore marine environment. Furthermore,

scour protection at the base of wind turbines offers supplementary hard habitats in areas of soft-bottom habitats, where most of the OFWs are installed in coastal waters (Krone et al., 2013).

As with all marine infrastructures, biofouling species rapidly colonize wind turbines and scour protections during a classical succession of stages (Degraer et al., 2020). Among the invertebrates, the barnacles are dominant species during the pioneer stage (0–2 years); this is followed by an intermediate stage (3–5 years) characterized by large numbers of several suspension feeding invertebrates, and a third “climax” stage (6+ years) when the plumose anemone (*Metridium senile*) and blue mussel (*Mytilus edulis*) dominate the community (Kerckhof et al., 2019). In the south of the North Sea, mainly in the Belgian Part of the North Sea, Kerckhof et al. (2019) has proposed the term “mytilisation” for the extensive colonization of the blue mussel on wind turbine structures. Large populations of blue mussel have also been observed on North-American OFWs (Hutchison et al., 2020).

Several authors had highlighted the role of OFW in the propagation and colonization of NIS. In this context, Kerckhof et al. (2011) showed that ‘OFWs in the Southern North Sea were rapidly colonised by non-indigenous species, particularly in the intertidal region’. They considered ‘that the new artificial hard substrata of the windmills offer new opportunities for non-indigenous species (introduced and southern Northeast Atlantic range-expanding species) to enter the Southern North Sea’ and ‘The non-indigenous species form an important part of the intertidal fouling community’. But Coolen et al. (2020) noted a low number of NIS on Halfweg, a concrete gas platform in the North Sea. They indicated that this structure does not act as a stepping stone for species invasions, i.e. connectivity between benthic-pelagic hard-bottom NIS populations. These authors

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Table 1

Summary of the information's on NIS (Non-Indigenous Species) or NNS (Non-Native species) extracted from the 25 analyzed documents classified in chronological order.

Reference	Location of the study	Direct observations	Only cited references or reference cited for NIS or NNS on OWF	Occurrence of NIS or NNS in the text	NIS or NNS reported	Title of the paper
Gill, 2005	–	No	No reference	0	0	Review of offshore renewable energy: ecological implications of generating electricity in the coastal zone
Glaby et al., 2007	Sydney Harbour, Australia	Yes	No reference	11	0	Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions?
Kerckhof et al., 2010	Southern North Sea	Yes	No reference	1	<i>Megabalanus coccopoma</i> ; <i>Perforatus perforatus</i> ; <i>Monocorophium acherusicum</i> ; <i>Crepidula fornicata</i>	Early development of the subtidal marine biofouling on a concrete offshore windmill foundation on the Thornton Bank (southern North Sea): first monitoring results
Kerckhof et al., 2011	Southern North Sea	Yes	Kerckhof et al., 2010	31	<i>Megabalanus coccopoma</i> ; <i>Perforatus perforatus</i> ; <i>Telmatogeton japonicus</i> ; <i>Austrominius modestus</i> ; <i>Jassa marmorata</i> ; <i>Hemigrapsus sanguineus</i> ; <i>Magallana gigas</i>	Offshore intertidal hard substrata: a new habitat promoting non-indigenous species in the Southern North Sea: an exploratory study
Bouma and Lengkeek, 2012	Southern North Sea	No	No reference	4	<i>Megabalanus coccopoma</i> ; <i>Perforatus perforatus</i> ; <i>Austrominius modestus</i> ; <i>Crepidula fornicata</i> ; <i>Caprella mutica</i> ; <i>Jassa marmorata</i> ; <i>Telmatogeton japonicus</i> ; <i>Magallana gigas</i>	Development of benthic communities on hard substrates within OWEZ, the first Dutch offshore wind farm
Kerckhof et al., 2012	Southern North Sea	Yes	Kerckhof et al., 2011	2	<i>Crepidula fornicata</i>	Comparison of the first stages of biofouling in two offshore wind farms in the Belgian part of the North Sea
Krone et al., 2013	Southern North Sea	Yes	Glaby et al., 2007; Kerckhof et al., 2012	1	<i>Magallana gigas</i>	Epifauna dynamics at an offshore foundation. Implications of future wind power farming in the North Sea
Adams et al., 2014	South-western Scotland	No	Glaby et al., 2007	0	0	Biological and hydrodynamic models to test Offshore marine renewable energy devices as stepping stones
de Mesel et al., 2015	Southern North Sea	Yes	Glaby et al., 2007	11	<i>Austrominius modestus</i> ; <i>Megabalanus coccopoma</i> ; <i>Jassa marmorata</i> ; <i>Hemigrapsus sanguineus</i> ; <i>Telmatogeton japonicus</i> ; <i>Perforatus perforatus</i> ; <i>Diplosoma listerianum</i> ; <i>Crepidula fornicata</i> ; <i>Magallana gigas</i>	Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species
Coolen, 2017	Southern North Sea	Yes	No reference	0	<i>Caprella mutica</i> ; <i>Monocorophium acherusicum</i> ; <i>Monocorophium sextonae</i> ;	Benthic biodiversity of artificial and rocky reefs in the Southern North Sea
Lengkeek et al., 2017	Southern North Sea	Yes	Coolen et al., 2018	39	<i>Fenestrulina delicia</i> ; <i>Smittoidea prolifica</i> ; <i>Diplosoma listerianum</i> ; <i>Diadumene lineata</i> ; <i>Crepidula fornicata</i> ; <i>Caprella mutica</i> .	Eco-friendly design of scour protection: potential enhancement of ecological functioning in offshore wind farms
Nall et al., 2017	Orkney, Scotland	Yes	Adams et al., 2014; Glaby et al., 2007; Kerckhof et al., 2011	31	<i>Corella eumyota</i> ; <i>Schizoporella japonica</i> ; <i>Amphibalanus improvisus</i> ;	Characterisation of the biofouling community on a floating wave energy device
Coolen et al., 2018	Southern North Sea	Yes	de Mesel et al., 2015	12	<i>Austrominius modestus</i> ; <i>Caprella mutica</i> ; <i>Megabalanus coccopoma</i> ; <i>Monocorophium sextonae</i> ;	Benthic biodiversity on old platforms, young wind farms, and rocky reefs

(continued on next page)

Table 1 (continued)

Reference	Location of the study	Direct observations	Only cited references or reference cited for NIS or NNS on OWF	Occurrence of NIS or NNS in the text	NIS or NNS reported	Title of the paper
					<i>Telmatogeton japonicus</i> ; <i>Fenestrulina delicia</i> ; <i>Smittoidea prolifica</i> ; <i>Diplosoma listerianum</i> ; <i>Crepidula fornicata</i> ; <i>Magallana gigas</i>	
Causon and Gill, 2018	European Seas	No	de Mesel et al., 2015; Gill, 2005; Glaby et al., 2007; Kerckhof et al., 2011	1	0	Linking ecosystem services with epibenthic biodiversity change following installation of offshore wind farms
Schutter et al., 2019	Southern North Sea	Yes	de Mesel et al., 2015	7	<i>Mnemiopsis leidyi</i>	Oil and gas platforms as artificial substrates for epibenthic North Sea fauna: effects of location and depth
Dannheim et al., 2020	European Seas	No	de Mesel et al., 2015; Coolen, 2017	5	0	Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research
Degraer et al., 2020	Southern North Sea	No	de Mesel et al., 2015; Glaby et al., 2007; Adams et al., 2014	12	<i>Telmatogeton japonicus</i> ; <i>Magallana gigas</i> ; <i>Crepidula fornicata</i>	Offshore wind farm artificial reefs affect ecosystem structure and functioning a synthesis
Hutchison et al., 2020	Eastern US coast	Yes	de Mesel et al., 2015	2	<i>Didemnum vexillum</i>	Offshore wind energy and benthic habitat changes: Lessons from Block Island Wind Farm
Coolen et al., 2020	Southern North Sea	Yes	Adams et al., 2014; Coolen et al., 2018; de Mesel et al., 2015	5	<i>Monocorophium sextonae</i> ; <i>Diplosoma listerianum</i>	Ecological implications of removing a concrete gas platform in the North Sea
Rumes and Kerckhof, 2021	Southern North Sea	No	No reference	2	<i>Perforatus perforatus</i> ; <i>Telmatogeton japonicus</i> ; <i>Magallana gigas</i>	Offshore wind farms as stepping stones for non-indigenous species
Kulkarni and Edwards, 2022	Worldwide Ocean	No	Causon and Gill, 2018	1	0	Bibliometric review on the implications of renewable offshore marine energy development on marine species
ter Hofstede et al., 2022	Southern North Sea	No	No reference	1	0	Offshore wind farms contribute to epibenthic biodiversity in the North Sea
Karlsson et al., 2022	North-eastern Scotland	Yes	de Mesel et al., 2015	4	0	Artificial hard-substrate colonization in the offshore Hywind Scotland Pilot Park
Farias Pardo et al., 2023	Worldwide Ocean	No	de Mesel et al., 2015 ; Lengkeek et al., 2017	3	0	Synthesis review of nature positive approaches and coexistence in the offshore wind industry
Spielmann et al., 2023	Southern North Sea	No	de Mesel et al., 2015; Coolen, 2017	5	0	Decommissioning of offshore wind farms and its impact on benthic ecology

underlined that ‘*The capacity of such structures to act as stepping stones, whereby species’ distributions are extended, depends on their depth together with species’ life history strategies*’. Finally, in their review, Degraer et al. (2020) noted that ‘*there are no published records of range expansion of subtidal non-indigenous species relating to the introduction of OWFs. While there is concern that OWFs may pose a threat to indigenous communities, this threat has yet to be demonstrated*’.

It is clear that NIS are able to colonize the wind turbine structures and scour protection of newly installed marine wind farms. But what are the available data on the NIS recorded on OWFs? If some NIS are considered as invasive species, and therefore problematic, do we have any data on this subject?

2. What are the non-indigenous species reported on offshore wind farm structures?

Our focus was limited to studies conducted on Offshore Wind Farms. Searches of documents were performed prior to June 20th, 2024 within “Web of Science” AND “Google Scholar” AND “Scindirect”. The following search query was used in the all-fields search: “offshore windfarm” OR “wind farm” OR “wind park” OR “windpark” AND “Non-Indigenous Species” OR “Nonindigenous Species” OR “Non-Native Species” OR “Nonnative Species”. All identified papers (publications and reports) were analyzed, i.e. full-text and reference list; but only the

marine invertebrates had been considered in this review.

Table 1 summarizes the information extracted from these documents classified in chronological order.

However, in his monograph on patterns of transoceanic marine biological invasions, Carlton (1987) makes no mention of NIS in relation to OWFs. In a later study, Gill (2005) reviewed offshore renewable energy and its ecological implications in the coastal zone, but provided no information or references on the occurrence of NIS. Glaby et al. (2007) are among the most cited authors evoking the NIS and OWFs, using the term NIS 11 times. Only 14 papers (56 %) are based on observations, while the others only contain references to papers citing NIS, which are often the same ones, i.e.: Glaby et al. (2007), de Mesel et al. (2015), Kerckhof et al. (2011), Adams et al. (2014) and Lengkeek et al. (2017) and Coolen et al. (2018). Apart from Hutchison et al. (2020), all the other papers reporting at least one NIS concern mainly the southern part of the North Sea (Belgium, the Netherlands and Germany). In the 15 papers citing at least one NIS, five report only one species, five report between two and four species, and five report more than five species. Most of the studies cited in the selected documents were not based on observations and several of the documents were based on the same references including papers without any relation to NIS (Table 1).

Kerckhof et al. (2011) is the best-known paper on the relationship between OFWs and NIS. These authors not only provide a list of the seven NIS collected on two Belgian OFW sites (C-POWER and

Table 2

List of the 19 NIS (Non-Indigenous Species) or NNS (Non-Native Species) reported in the 25 documents analyzed with indication of their taxonomy, date of first record in the North-eastern Atlantic and their native origins.

Species	Taxonomy	Date of first record in the NE Atlantic	Native Range
<i>Telmatogeton japonicus</i> Tokunaga, 1933	Insecta Diptera	1960	North-western Pacific
<i>Amphibalanus improvisus</i> (Darwin, 1854)	Crustacea Cirripedia	1827	North-western Atlantic
<i>Austrominius modestus</i> (Darwin, 1854)	Crustacea Cirripedia	1945	New-Zealand
<i>Megabalanus coccopoma</i> (Darwin, 1854)	Crustacea Cirripedia	1851	Central and eastern Pacific
<i>Caprella mutica</i> Schurin, 1935	Crustacea Amphipoda	1994	North-western Pacific
<i>Jassa marmorata</i> Holmes, 1905	Crustacea Amphipoda	1910	North-western Atlantic
<i>Monocorophium acherusicum</i> (Costa, 1853)	Crustacea Amphipoda	1937	Unknown
<i>Monocorophium sextonae</i> Crawford, 1937	Crustacea Amphipoda	1930	Unknown
<i>Hemigrapsus sanguineus</i> (De Haan, 1835)	Crustacea Decapoda	1992	North-western Pacific
<i>Crepidula fornicata</i> (Linnaeus, 1758)	Mollusca Gastropoda	1870	North-western Atlantic
<i>Magallana gigas</i> (Thunberg, 1793)	Mollusca Bivalvia	1965	North-western Pacific
<i>Mnemiopsis leidyi</i> A. Agassiz, 1865	Ctenophora Tentaculata	2005	North-western Atlantic
<i>Diadumene lineata</i> (Verrill, 1869)	Cnidaria Actinaria	1890	Pacific
<i>Fenestrulina delicia</i> Winston, Hayward & Craig, 2000	Bryozoa Cheilostomatida	2005	North-western Atlantic
<i>Schizoporella japonica</i> Ortmann, 1890	Bryozoa Cheilostomatida	1976	North-western Pacific
<i>Smittioidea prolifica</i> Osburn, 1952	Bryozoa Cheilostomatida	2008	East Pacific
<i>Corella eumyota</i> Traustedt, 1882	Chordata Ascidiacea	2002	Southern Ocean
<i>Diplosoma listerianum</i> (Milne-Edwards, 1841)	Chordata Ascidiacea	1840	Unknown
<i>Didemnum vexillum</i> Kott, 2002	Chordata Ascidiacea	2010 (NW Atlantic)	North-western Pacific

BELWIND), but also divide the semi-quantitative abundances of the species into six classes: S, superabundant; A, abundant; C, common; F, frequent; O, occasional; R, rare. Only two species are classified as S: the barnacle *Perforatus perforatus* and the insect *Telmatogedon japonicas*; the barnacle *Austrominius modestus* is classified as A; the barnacle *Megabalanus coccopoma* and the amphipod *Jassa marmorata* are both classified as C; while the crab *Hemigrapsus sanguineus* is classified as F and the oyster *Magallana gigas* as *de Mesel et al. (2015)* has also applied the semi-quantitative abundance scale of *Kerckhof et al. (2011)*, attributing the barnacle *Perforatus perforatus* from C to S, and the insect *Telmatogedon japonicas* to S, the barnacle *Austrominius modestus* to A; the barnacle *Megabalanus coccopoma* and the amphipod *Jassa marmorata* to A, the crab *Hemigrapsus sanguineus* to F and the oyster *Magallana gigas* to O. Both *Kerckhof et al. (2011)* and *de Mesel et al. (2015)* obtain similar classification results. *Nall et al. (2017)* estimated that NIS represented 4.1 % of the species richness and 0.1 % of the mean biomass in the quantifiable samples from offshore Hywind Scotland Pilot Park. Surprisingly, there are no data on the exact abundances of NIS on turbine foundations or scour protections.

Apart from the larvae of the insect *Telmatogedon japonicus* reported only in the southern part of the North Sea, barnacles are known to be pioneer species showing very high abundances on new artificial structures, with densities reaching more than 30,000 ind.m² some months after the immersion of ARs (*Dauvin et al., 2021*).

A total of 19 NIS, including 12 sessile and seven motile species, has been reported on OWFs (Table 2). Most of them have been reported in European waters for a long time, in any case before the first implementation of OWFs. No new introduction can be attributed to OFW development. For the European waters, NIS originate from two main regions: the North-western Pacific and North-western Atlantic. Since 1970, 640 NIS (excluding microalgae, pathogens and parasites) have invaded European waters, with an increasing average annual rate of new introductions.

(<https://www.eea.europa.eu/en/analysis/indicators/marine-non-indigenous-species-in>). So, the number of NIS reported on OWFs is very low and represents only 3 % of the NIS reported in European waters.

3. What would we need for future research?

It is clear that the available data do not support the assumed role of OWFs in the expansion of benthic NIS. OFW infrastructures offer two kinds of benthic habitat which are colonized by mobile and sessile biofouling species. Among them, some are Non-Indigenous Species. Nevertheless, their numbers remain very low: only 18 NIS for European

waters and one for north-eastern American waters. This review shows that there is no established evidence for a relationship between the implementation of OFWs and the colonization of NIS on OFW. Less than 3 % of the NIS registered at the scale of the European waters had been reported on OWFs. Only few species mainly barnacles and amphipods had been reported by *Kerckhof et al. (2011)* and *de Mesel et al. (2015)* as abundant on OFW structures, but these species are known to be pioneer species able to colonize all the artificial structures immersed in the marine environment (*Dauvin et al., 2021*). No non-native species specific to offshore wind farms have been identified.

So, in the future, to assess the role of OFWs as stepping stones in the expansion and proliferation of NIS, we need to dramatically increase the number of observations: i.e. to promote the identification of all biofouling species present on OFW infrastructures. This would involve not only quantifying the NIS present, but also compiling data on the abundance per unit surface area. This is an evidently absence of quantitative data on the abundance of biofouling species including NIS colonising the OFW infrastructures.

Nowadays, OWFs are being developed along the north-eastern European seaboard from the southern Bay of Biscay in France to the English Channel as well as in the North Sea and Norwegian Sea, and also in several countries bordering the Baltic Sea. This provides an opportunity to encourage a collaborative project on OFW which would have two main objectives: 1) to survey the northern progression of benthic species in relation to the increase of seawater temperature in this part of the North Atlantic (linked with Climate Change) and 2) to assess the precise impact of OFWs on the colonization and expansion of NIS due to human activities. Future wind farms, at least in France, may be quite far from the coast (up to 50 km), so they will offer structures to be colonized offshore, isolated from many other human activities. The study of biofouling colonization processes in these offshore habitats represents a new ecological challenge for the scientific community.

CRedit authorship contribution statement

Jean-Claude Dauvin: Writing – original draft, Conceptualization.

Declaration of competing interest

No interest statement.

Data availability

No data was used for the research described in the article.

Acknowledgements

I thank Caen University and the Centre National de la Recherche Scientifique (UMR 6143 M2C CNRS) for welcoming me as at the M2C laboratory. I also thank Michael Carpenter for editing the English style and grammar of this paper.

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