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Biofouling prevention and management in offshore renewable energy infrastructure and construction

Best Practices in Biofouling Management - Volume 3

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Published in 2024 by the United Nations Educational, Scientific and Cultural Organization, 7, place de Fontenoy, 75352 Paris 07 SP, France, in collaboration with the International Maritime Organization.

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The publication should be cited as follows: IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships. 2024. *Best Practices in Biofouling Management. Vol. 3: Biofouling prevention and management in offshore renewable energy infrastructure and construction*. Paris, IOC-UNESCO and IMO. (IOC Technical Series, 174)

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Graphic Design: Noam Le Pottier
Cover photo : © Mike Mareen/Shutterstock
Printed in UNESCO printshop, Paris, France

(IOC/2024/TS/174Vol.3)

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Volume 3

Best Practices in Biofouling Management

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This report is designed to assist environmental managers, policymakers, and other responsible parties within the new offshore renewable energy (ORE) industry to develop and implement effective processes to manage the spread of invasive aquatic species (IAS) associated with biofouling. The document reviews the issues associated with biofouling on structures, infrastructure, and equipment in this rapidly evolving and expanding industry including current issues and those that may appear in the near future. Gaps in biofouling management in the ORE industry are identified, and recommendations for control, limitation of spread, and proactive avoidance of appearance of new biofouling IAS are suggested.

Considering the complexity of offshore developments and the diversity of equipment and infrastructure mobilized throughout the life span of a project, this report does not provide detailed advice regarding the management of specific assets or vessel types. Instead, the focus is on providing a summary of effective approaches to biofouling management and developing overarching management plans that address the full scope of biofouling-related risks at the scale of the entire project. Such plans need to clearly identify the acceptable standard of biofouling management for vessels and infrastructure operating within the project area and provide clear advice on the application of biofouling management tools to ensure this standard is maintained. Furthermore, overarching plans should provide decision-support tools that clearly identify biofouling management pathways to assist contractors in understanding what options are available to them, and to ensure that proactive management approaches are considered well in advice of mobilization.

As with offshore oil and gas projects, offshore renewable efforts will operate across multiple jurisdictions, and considering the global nature of the industry, this document does not provide guidance for specific biofouling management standards that should be applied to offshore operations or review relevant regulations. It is the responsibility of the offshore renewable energy operators (or titleholders) to ensure that overarching plans and all operations supporting a project address applicable regulatory requirements and that plans are approved by relevant authorities.

Report team

Authors

Dr Simone Dürr, School of Biological and Environmental Sciences, Liverpool John Moores University, UK

Prof. Sandra E. Shumway, Department of Marine Sciences, University of Connecticut, USA

Research Associates

Noreen Blaschik, Department of Marine Sciences, University of Connecticut, USA

Eric Heupel, Department of Marine Sciences, University of Connecticut, USA

Industry Survey Data Provider

Tina Liu, World Ocean Council

Editors

Pia Haecky, Intergovernmental Oceanographic Commission of UNESCO

John Alonso, International Maritime Organization

Lilia Khodjet El Khil, International Maritime Organization

Henrik Enevoldsen, Intergovernmental Oceanographic Commission of UNESCO

External Reviewers

Dr. Andrew Want, University of Hull, UK

Prof. Daniel Rittschof, Duke University, USA

Proofreader

Julie Wickenden

Acknowledgements

This publication has been prepared through a collaboration between IOC-UNESCO, the GEF-UNDP-IMO GloFouling Partnerships and the World Ocean Council.

The following companies and people are acknowledged for their input and help:

Representatives from SSE, Vattenfall

Consultancy firms – Anchor Environmental, RPS, Campbell Ocean Data

People – Aiden Biccard, Peter Crockett, Peter Enderlein, Robert Edyvean, Jesse Van Der Grient, John Lewis, Andrew Morris, Christopher McQuaid, Kirsty McQuaid, Chris Nall, Tammy Robinson-Smythe, Daniel Rittschoff, Geoffrey Swain, Travis Washburn, Andrew Want, Helena Wiklund

GloFouling Partnerships

Building Partnerships to Assist Developing Countries to Minimize the Impacts from Aquatic Biofouling (GloFouling Partnerships) is a collaboration between the Global Environment Facility (GEF), the United Nations Development Programme (UNDP) and the International Maritime Organization (IMO). The project aims to develop tools and solutions to help developing countries to reduce the transfer of aquatic invasive species through the implementation of the IMO Guidelines for the control and management of ships' biofouling. www.glofouling.imo.org

Funding Agency

GEF - the Global Environment Facility - a multilateral fund dedicated to confronting biodiversity loss, climate change, pollution, and strains on land and ocean health. Its grants, blended financing, and policy support helps developing countries address their biggest environmental priorities and adhere to international environmental conventions. The GEF connects 185 member governments with sustainability leaders across civil society, Indigenous Peoples, and the private sector, and works closely with other environmental financiers for efficiency and impact. Over the past three decades, the GEF has provided more than $22 billion in grants and blended finance and mobilized $120 billion in co-financing for more than 5,000 national and regional projects. www.thegef.org

Implementing Agency

UNDP – the United Nations Development Programme – partners with people at all levels of society to help build nations that can withstand crisis, drive and sustain the kind of growth that improves the quality of life for everyone. On the ground in nearly 170 countries and territories, to eradicate poverty and reduce inequality. We help countries to develop policies, leadership skills, partnering abilities, institutional capabilities, and to build resilience to achieve the Sustainable Development Goals. Our work is concentrated in three focus areas: sustainable development; democratic governance and peace building; and climate and disaster resilience. www.undp.org

Executing Agency

IMO - the International Maritime Organization – is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships. www.imo.org

Executing Partner

IOC UNESCO - the Intergovernmental Oceanographic Commission of UNESCO - is the United Nations body responsible for supporting global ocean science and services. IOC is partnering with IMO in implementing the non-shipping elements of the GloFouling Partnerships project. https://ioc.unesco.org

Biofouling on anthropogenic structures poses a serious threat to the marine environment as a result of the role it plays as a vector for the introduction, establishment and/or spread of IAS globally, and offshore energy structures can provide expanded opportunities for dispersion of IAS.

As with all other industries impacted by biofouling, the ORE sector will need to address environmental, economic and social issues associated with IAS invasions. There is a unique opportunity for the newly developing offshore industries to address these threats in a proactive fashion through the establishment of research collaborations with other actors (such as scientists/academia), development of technologies and gear designed to deter biofouling, development of biofouling management plans that incorporate control measures, as well as support of education efforts.

While there are a multitude of methods and products available to combat biofouling, there will never be one universal solution. The best path forward is through open and transparent cooperation between all stakeholders coupled with an international awareness campaign, establishment of a comprehensive and accessible IAS database and enforceable regulations, all of which will serve to minimize environmental damage associated with IAS.

For further information on the GloFouling Partnerships Project please contact:

GloFouling Partnerships Project Coordination Unit
Department of Partnerships and Projects
International Maritime Organization (IMO)
4, Albert Embankment, London, SE1 7SR, United Kingdom
Email: glofouling@imo.org
Web: https://www.glofouling.imo.org/

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Photo : Dr. Andrew Want, Université de Hull


@Oscar Bos, Wageningen Marine Research

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Introduction

This report reviews the available scientific research and industry information regarding biofouling, invasive aquatic species (IAS), and biofouling management in new and emerging maritime industries with offshore structures and infrastructure: 1) renewable energy generators (wind, tidal, wave, solar); 2) pipelines, cables, pipes; 3) monitoring stations and buoys; 4) mining; and 5) mobile associated equipment (support vessels, ROV, AUV). Knowledge gaps are identified and recommendations are presented to guide future efforts to limit or reduce biofouling and expansion of IAS.

Comprehensive biofouling management plans (BFMP) for infrastructure or vehicles of maritime industries are important tools to mitigate risks from biofouling, as biofouling causes many problems and issues for industries and the environment, has significant economic costs to control, and can indirectly (through the spreading of IAS) have far-reaching negative effects on livelihoods and damage environmental and human health. Biofouling causes (and can exacerbate) corrosion, material fatigue, and results in increased drag, fuel consumption and associated emissions, thus contributing significantly to global climate change (GCC) (Poloczanska and Butler, 2010). By way of example, authors from the US Department for Naval Architecture and Ocean Engineering (Schultz et al., 2011) estimated that the economic impact of biofouling for the US DDG-51 fleet[1] alone was US$56 million per year. Historic measures to mitigate biofouling have been seen to have unintended impacts on non-target species, food security and human health, and innovative solutions are therefore needed.

In addition to the issues described above, biofouling can also result in the translocation of non-native species to new areas and regions. Mineur et al. (2012) (among others) called these 'invasive alien species'; however, the acronym IAS in the *IMO 2023 Guidelines on Biofouling Management* refers specifically to 'invasive aquatic species', which is defined as 'non-native species to a particular ecosystem which may pose threats to human, animal and plant life, economic and cultural activities, and the aquatic environment' (IMO, 2023). Therefore, in this report IAS refers to invasive aquatic species and the term invasive alien species (which includes terrestrial species) will be referred to as non-native invasive species (NIS)[2] for clarity.

IAS may change the ecosystem, contribute to biodiversity loss and disease and parasite and pathogen infestation in local marine communities. As a result, UN Member States agreed on actions in their Agenda 2030 against these impacts with their Sustainable Development Goals (SDG), particularly SDG 13 (Climate Action), SDG 14 (Life below water) and their inclusion in the United Nations Convention on the Law of the Sea (UNCLOS), the IMO Ballast Water Management Convention, the IMO Biofouling Guidelines,

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[1] *Consisting of 56 ships in 2009*

[2] *Additional terminology used in the scientific literature includes 'invasive non-native species' (INNS), 'neobiota', 'exotic species', 'immigrant species and 'non-indigenous' species, among others.*

the Convention on Biological Diversity (CBD), and the Convention on Climate Change (UNFCCC). Very recently, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) reported that invasive species in general contributed to more than half of all global species extinctions and recommended options for management and governance responses (Roy et al., 2023). Thus, a biofouling management plan detailing how biofouling can and is being managed is an essential tool as a minimum for every maritime industry to support these actions. In shipping, progress has been made even before Agenda 2030 with the adoption of MEPC 62/24/Add.1, Annex 26 Resolution MEPC.207(62) in 2011, which consisted of guidelines on the control and management of ship biofouling to minimize the transfer of IAS via the most common vectors. These guidelines were subsequently updated and amended in 2023 (Resolution MEPC.377(80)). Despite this, however, there are currently no biofouling management guidelines on IAS available from the IMO which deal with elements of the maritime industry beyond the included definition of a 'ship',[3] e.g., new and emerging maritime industries such as wind turbines.

As guidelines, the measures contained in the resolution are not mandatory and there is room for improvement in their implementation by adoption into (and subsequent enforcement of) national legislation/regulations. In addition, other maritime industries that are prone to biofouling would benefit from clear and specific guidelines.

One of the major problems with biofouling management is that biofouling can occur everywhere where there is an

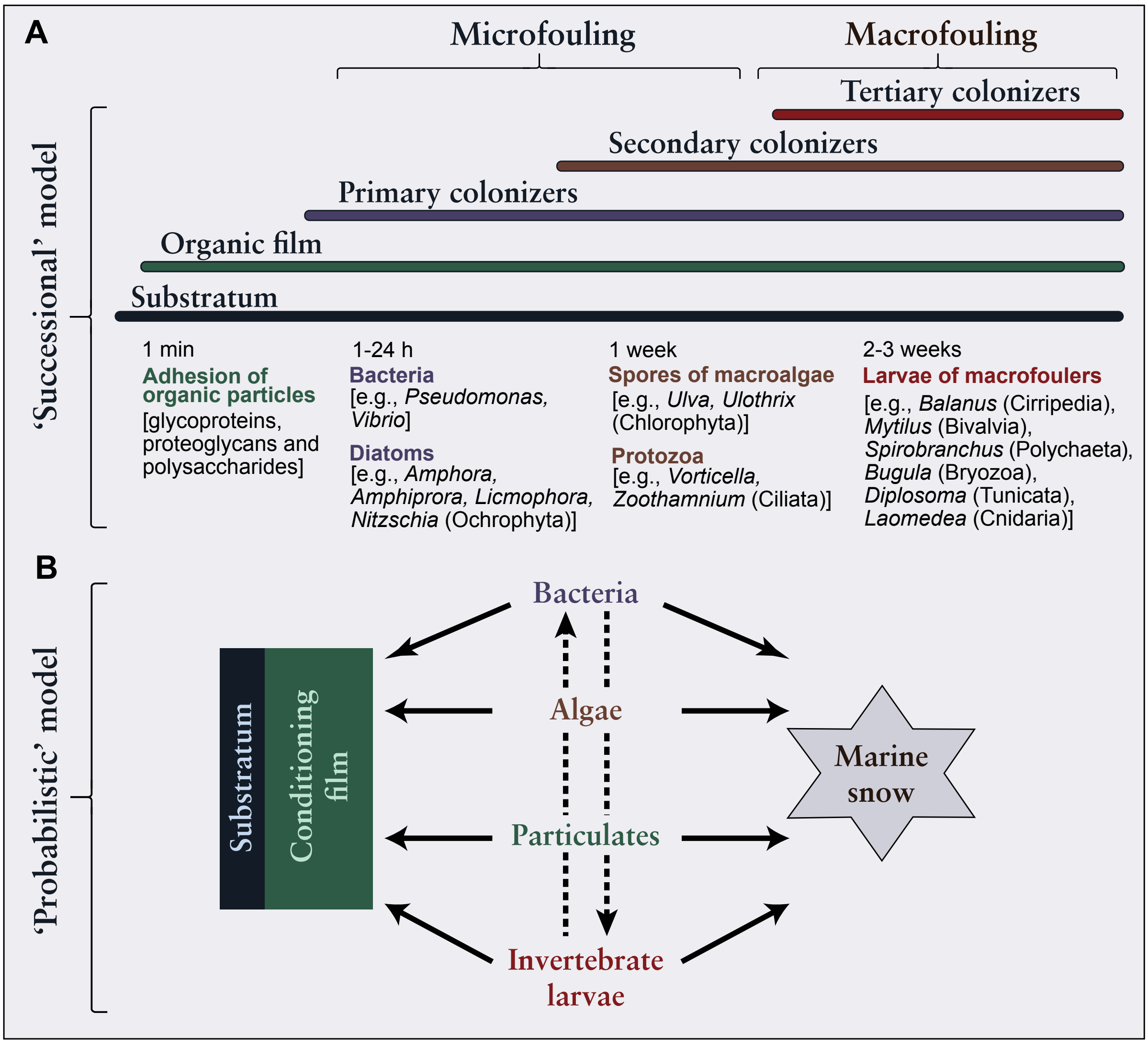

Figure 1. Schematic models of marine biofouling colonization: a) 'successional' and b) 'probabilistic'. Note that the time periods for biofouling are generalizations; larvae will settle at will and can do so without a biofilm.

Source: Vinagre et al., 2020

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[3] *According to the guidelines, a 'ship' refers to 'a vessel of any type whatsoever operating in the aquatic environment and includes hydrofoil boats, air-cushion vehicles, submersibles, floating craft, fixed or floating platforms, floating storage units and floating production storage, and off-loading units' (IMO, 2023).*

interface with seawater and natural or artificially produced or shaped material (Wahl, 1989; Dürr and Thomason, 2010). Marine biofouling species are mostly sessile (invertebrates; algae), often colonial, living on natural or artificial surfaces, and reproducing via larvae and spores (Crisp, 1984; Havenhand and Styan, 2010). Gametes are either fertilized internally and released or fertilized in the water column. While these dispersal stages grow into larvae, the length of time spent in the water column varies depending on the species, hydrography, and other environmental factors (McQuaid and Miller, 2010). While they may undergo multiple larval stages and travel vast distances, the initial larva or spore usually disperses close to the parent. In order to settle, the larva has to have access to a suitable surface to metamorphose into a juvenile (this is referred to as 'recruitment') and later, to a reproductive adult.

Different species have different surface requirements, e.g., presence or absence of a biofilm, physical characteristics, chemistry, and light regime. Larvae and spores are not always produced throughout the year and their production varies in distinct regions: polar, cold-temperate, warm-temperate, and tropical regions. For example, cold-temperate species do not usually reproduce in autumn and winter, while tropical species may reproduce throughout the year or in relation to the monsoon. If the surface encountered for settlement is moving (e.g., a ship), the likelihood for the larvae to settle successfully and metamorphose is reduced, but when the surface is stationary (e.g., at anchor or tied up in port), the rate of successful settlement increases (see Crisp, 1984 for review on the role of larvae as key to biofouling). If a ship stops in multiple locations locally, regionally, or even after crossing the equator, a mix of larvae of species encountering that material may settle, recruit, and grow to adults – even though these species may not mix on material that is permanently static. As different species release their larvae and propagules at different times, this results in different groups of species (community, assemblage) found on materials depending on when the artificial material was exposed to seawater. The development or succession of that community will also be influenced by the time period of exposure to that specific environment. The traditional sequence of succession on a new surface in the marine environment is determined in theory as different steps (Wahl, 1989; Figure 1) with macromolecules adhering first, followed by organisms such as bacteria and ciliates, then single-celled algae such as benthic diatoms, and finally invertebrates (as larvae or growth from the sides) and algae. These steps are observed in real time in the field, but there are occasions where invertebrates settle even before bacteria (Rittschof, 2023).

Colonization of surfaces by larvae and spores of biofoulers is very dynamic. In many environments, especially in warmer waters, there is a virtually continuous assault of settlement-stage organisms from the time the surface is immersed until it is removed from the water. Settlement of one organism may impact another organism as in facilitation, inhibition, and tolerance (Connell and Slatyer, 1977). The biofouling organisms recruited after metamorphosis are exposed to numerous factors such as competition, predation, and local hydrography, all of which will impact the resultant biofouling community composition, structure, and dynamics. When free space is opened up, it is rapidly colonized by new settlers. Many species that become biofouling recruits are strong opportunists with extensive larval spat falls that grow rapidly to reproductive stage (some as fast as three weeks) upon settlement and can swamp every surface. That leads to monocultures of certain dominant and invasive species (e.g., *Mytilus* species, various cirripede species) on artificial surfaces with very low diversity (Dürr and Wahl, 2004).

There are currently no coatings or practices that are 100% effective in eliminating biofouling. Experience with biocidal biofouling approaches over the centuries has led to restrictions in the use of compounds that damaged ecosystems. These include arsenic, lead and, most recently, the TBT (tributyltin) coatings, which are prohibited by the International Convention on the Control of Harmful Anti-fouling Systems on Ships (IMO, 2009). Biofouling has existed since humanity put structures (wooden and manufactured) in seawater. Early biofouling management included cleaning, tar coatings, and copper cladding (Finnie and Williams 2010). Currently, biofouling management (Box 1) includes mostly the corner stone instruments: 1) cleaning and husbandry; 2) biocides in solution and in coatings (antifouling); and 3) easy-clean surfaces that are usually near the critical surface energy for weak bioadhesive bonds (foul-release at the critical surface energy the bioadhesive minimum). Cleaning and husbandry efforts include air-drying, brushing, high water pressure, and AUV (autonomous underwater vehicles). Biocidal antifouling coatings are often copper-based, but can incorporate other co-biocides (even natural compounds) and catalysts, including tin[4] (Finnie and Williams, 2010). Co-biocides are added because many environmental regulations limit the amounts of copper ions that can be released from the coating per day and the levels may not be sufficient to prevent biofouling by certain copper-resistant species like barnacles.

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[4] *Although it should be noted that use of organotin compounds, which act as biocides in antifouling systems, is prohibited by the Antifouling Convention (IMO, 2009)*

BOX 1. Biofouling management best practices transferable to offshore industries

Biofouling management is essential in any maritime industry to manage the spread of IAS and counteract biodiversity loss (Roy et al., 2023). Biofouling management is rarely applied to offshore structures; in fact, there may be no actual biofouling management plan in place, particularly for wind farms. Often, biofouling is not seen as a risk for IAS introduction or spread of invasive species, and risk management plans for offshore structures (e.g., SSE Renewables, 2022a, b) and artificial reefs are encouraged. Offshore industries that are only in the developmental state (e.g., tidal and wave energy) are concerned with biofouling issues and IAS, and are testing biofouling mitigation options (e.g., antifouling coatings, husbandry, and cleaning). The issues associated with biofouling are well known in shipping and aquaculture, including corrosion, material fatigue, drag, roughness, weight load, stock species death, introduction of pathogens, parasites, biofouling IAS, and increased fuel needs and emissions (GEF-UNDP-IMO GloFouling Partnerships Project and GIA for Marine Biosafety, 2022a,b). These issues are similar for offshore structures. The mitigation of biofouling and thus biofouling IAS are manyfold in these industries, and predominantly consist of antifouling coatings containing biocides (some self-polishing), foul-release coatings with biocides, husbandry, and cleaning (see Table 1). There is a rich literature available on efforts to control biofouling in the marine environment; however, most of it is focused on boats, marinas, aquaculture, and other coastal operations (e.g., Dürr and Thomason, 2010; IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships, 2022a,b). To date, no antifouling paint or coating has proven fully efficient at preventing biofouling (see Hemery, 2020), and another downside of these options is that they contribute to pollution with biocide leachate and microplastic ablation, as well as possible introduction of IAS into the ecosystem brought about by in-water cleaning (Ruiz et al., 1999; Bax et al., 2003; Molnar et al., 2008; Atalah et al., 2016). Thus, the call for 'environmentally friendly' options is getting stronger (Yan et al., 2000; Gu et al., 2020; Liu et al., 2022; Rittschof, 2023). New sustainable innovative antifouling options were demanded by Liu et al. (2022) (Figures 2,3) and even some environmentally 'safe' biocides may be considered as environmentally friendly alternatives (see Table 1). Many of these coatings and materials require regular cleaning; however, technology is taking giant steps with robotics and AI, such that IAS are not released into the sea. Management approaches are numerous (see Figures 19, 21) and the oil and gas industry may inform on management of support vessels and offshore structures (see Figures 20, 27). Work has already begun towards biofouling management of static structures in the new offshore industries (e.g., Hopkins et al. 2021a,b). Biofouling management for floating offshore structures may need to be site-specific, as biofouling is site-specific (Macleod et al., 2016; Want and Porter, 2018; Want et al., 2019), as is best practice in finfish aquaculture (Dürr and Watson, 2010). If deployment and maintenance times are carefully scheduled with biofouling settlement times (e.g., Kerckhof et al., 2010; Nall et al., 2022), this could serve as a means of controlling biofouling and subsequent IAS. This approach may be aided by monitoring and knowledge of settlement patterns (succession). Use of current antifouling paints is impractical on windfarm pylons due to their efficacy time-frame (Tiron et al., 2015). Removal of other devices from the environment for cleaning may be unrealistic owing to weather and environmental conditions. The literature available specifically regarding control of biofouling on offshore renewable energy structures is limited so, while some existing methodologies may be applicable to these offshore structures and operations, there will also be a need to develop specific methodologies as the industry matures.

Antifouling coatings are often ablative and self-polishing (SPC), and experimental coatings can encapsulate biocides and enzymes. Hydrophobic or amphiphilic foul-release coatings do not contain biocides but currently represent a very small percentage of the commercial market. Presently, these less toxic coatings only work while the vessel moves at a certain speed, meaning that when in port, neither the ship nor the local environment is protected from biofouling or species transfer. In recent years, the trend has moved towards use of antifouling foul-release coatings (Rittschof, 2023), some contain biocides just as in antifouling coatings, others carry the biocide as the catalyst. Liu et al. (2022) discuss innovative and sustainable antifouling approaches and the impact of biocidal antifouling strategies (Figures 2 and 3) which may inform future antifouling coatings. While new coatings or other means of repelling biofouling

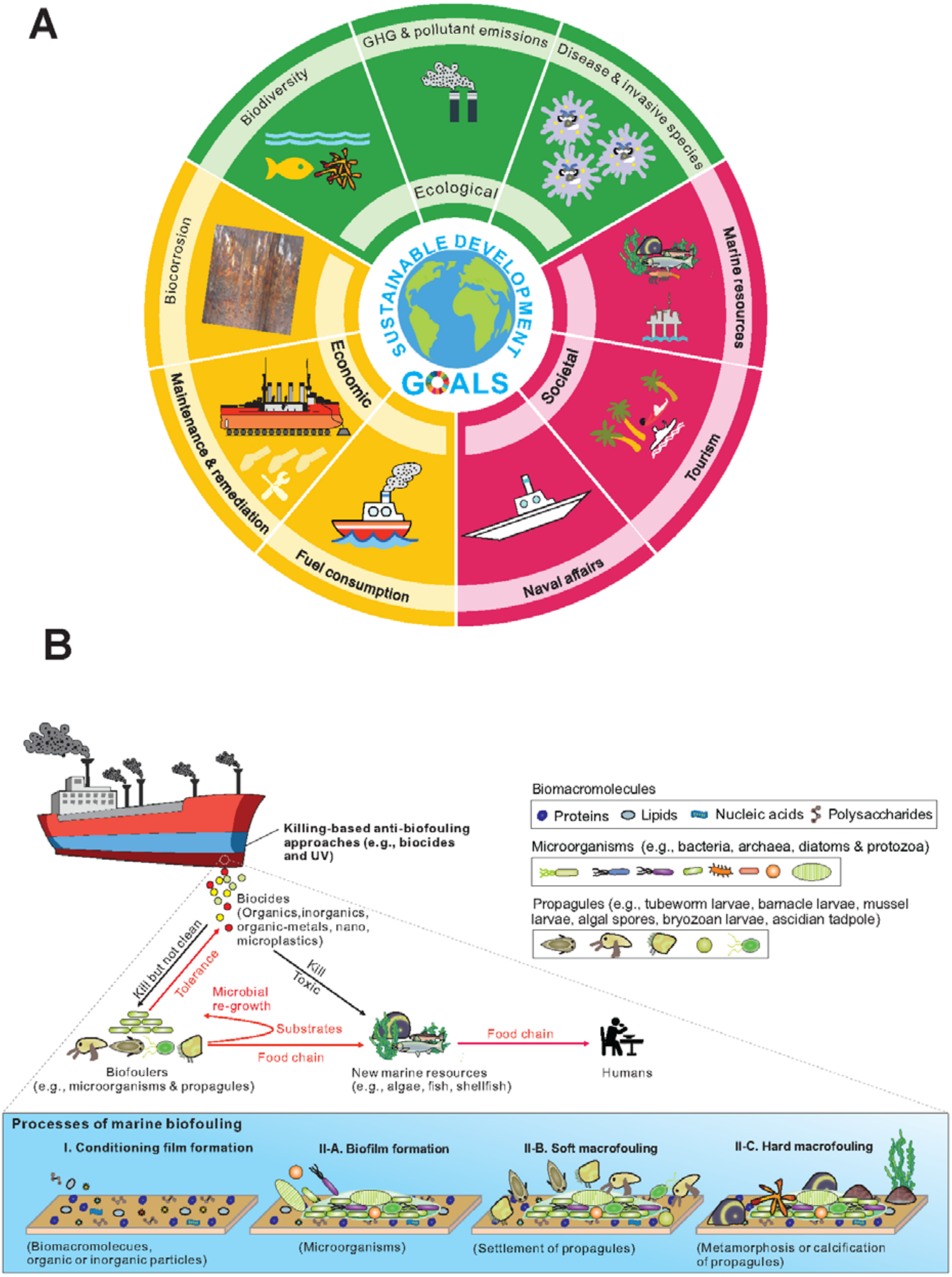
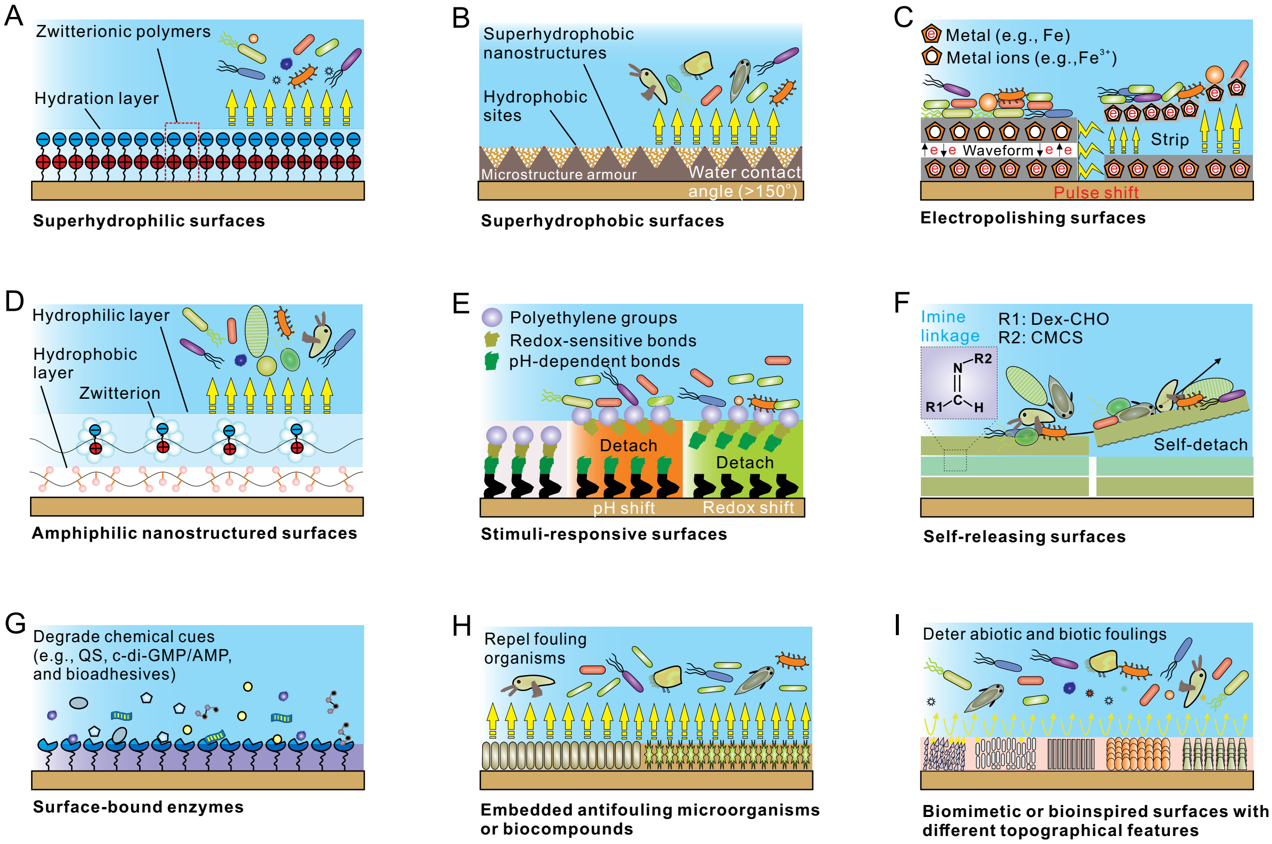


Figure 2. Impacts of marine biofouling and conventional killing-based strategies on sustainable development. (A) The impacts of marine biofouling on sustainable development are assessed from the viewpoint of the three pillars (ecological, societal, and economic) of sustainability involved in the major marine activities. Costs include: increased fuel consumption associated with hydrodynamic drag and emissions (e.g., greenhouse gas, carbon particulates, and toxic metals); decreased performance and operational lifespan of ships, marine installations, and facilities caused by biocorrosion; maintenance and cleaning; introduction of invasive species and diseases; and loss of biodiversity and ecosystem function. (B) Processes of marine biofouling and impacts of conventional killing-based antibiofouling strategies on marine ecology. Both soft (e.g., macroalgae, sea squirts, hydroids) and hard foulants (e.g., barnacles, tube worms, mussels) are included.

Source: Liu et al., 2022.



Superhydrophilic surfaces

Superhydrophobic surfaces

Electropolishing surfaces

Amphiphilic nanostructured surfaces

Stimuli-responsive surfaces

Self-releasing surfaces

Surface-bound enzymes

Embedded antifouling microorganisms or biocompounds

Biomimetic or bioinspired surfaces with different topographical features

Figure 3. Selective examples of innovative sustainable antifouling approaches. These examples are selected from (A) to (C) physically or physiochemically, (D) to (F) chemically and (G) to (I) biologically based solutions. The performances noted are only based on repelling biofouling organisms, acknowledging that many options exist (see Table 1), including biocides that are environmentally safe. All materials used for antibiofouling should be ecofriendly or biodegradable. Zwitterionic polymers have both positive and negative charges incorporated into their chemical structures. Abbreviations: c-di-GMP/AMP, cyclic di-GMP/AMP; CMCS, carboxymethyl chitosan; Dex-CHO, dextran aldehyde; QS, quorum sensing. Expanded development of new antifouling technologies is a continuing field of research.

Source: Liu et al., 2022.

organisms are developed, current methods, some used in concert, will need to be applied and are part of best practice and biofouling management plans (see Table 1) for artificial materials to, for example, reduce emissions, corrosion, material fatigue, diversity loss, and death of food species.

Opportunistic biofouling species have the capability to 'hitchhike' and may get a lift to a new environment by mobile structures in the marine environment, for example by a ship (one of the main vectors for IAS) on an intercontinental route. This is most likely to happen after the vessel or the mobile structure has been stationary, (e.g., in a port) for an extended period and then moved to a new location. A larva may just need a few hours to metamorphose into a juvenile (e.g., tunicates) on an area as small as half a square millimetre on an unprotected hull. When the vessel is en route, the organisms will be 'on hull' hitchhikers. If the juvenile survives to become a reproductive adult, then at the next stop it may release propagules which are ready to 'invade' a local surface (Herbert et al., 2003; Bulleri and Airoldi, 2005; Sammarco et al., 2012; Hawkins et al., 2008, 2009; Nall et al., 2015; Krone et al., 2013; De Mesel et al., 2015; Bishop et al., 2017) and could establish a new population (see Box 2). If that species is not part of the ecosystem, but can survive and thrive, it becomes an IAS and may then infiltrate to become part of the local communities. Due to their opportunistic, invasive, and dominant nature, IAS may overwhelm other species in the local community and may lead to their local extinction (Roy et al., 2023), thus changing the structure (function), composition, and dynamics of the local community (Apte et al., 2000; Floerl et al., 2009; Saura et al., 2014; Nall et al., 2015). The extinction rate of species, and therefore diversity loss, in a community (and then the ecosystem) is faster if local species are challenged, particularly physiologically directly or indirectly, as a result of GCC (e.g., marine heat waves), pollution (biocides, microplastics, nutrients), or habitat loss. The 'jump' by IAS into the new community is mostly not straight off the vector (the transport ship), so does not implement the invasion instantly, but in 'steps'. The first place to jump ship for the future IAS may be the

BOX 2. Biofouling IAS spread on offshore structures

Biofouling species are opportunistic and colonize artificial surfaces quickly and successfully (Brodin and Andersson, 2009; Ruiz et al., 2009); they are expanding at an unprecedented rate with the development of offshore structures (ocean sprawl: Firth et al., 2016). The expansion of offshore energy systems provides a network of structures that will facilitate settlement, population growth, and potential dispersion of biofouling IAS (Herbert et al., 2003; Bulleri and Airoldi, 2005; Sammarco et al., 2012; Hawkins et al., 2008, 2009; Nall et al., 2015; Krone et al., 2013; De Mesel et al., 2015; Bishop et al., 2017). The IAS arrive in the region on passive global vessel transport (e.g., via the shipping pathway; see IUCN (2017) for more information on definitions) and first infiltrate local biofouling communities, spreading from there into the network of artificial structures until they finally become part of the communities on natural surfaces. Thus, it can be assumed that the biofouling communities on offshore structures, such as windfarm pylons, include IAS components and therefore are of ecological concern for the ecosystem (as shown in Page et al., 2006; Ferreira et al., 2006; Wilson and Elliott, 2009; Kerckhof et al., 2011; Bouma and Lengkeek, 2009). Given the limited survey data on biofouling on these structures, there is little information available on species composition, dispersal dynamics between offshore structures, or origin of IAS. The limited information is shown in Table 3. As the biofouling IAS disperse their larvae and algal propagules, it is assumed that these IAS will spread between offshore structures (e.g., windfarm pylons) and from there potentially further distances. Thus, each substructure and each structure is a potential **stepping stone for IAS** (Boehlert and Gill, 2015; Shields et al., 2011; Adams et al., 2014; Bishop et al., 2017) to relocate into the local ecosystem and change its composition, dynamics, structure, and instigate local diversity loss (Apte et al., 2000; Floerl et al., 2009; Saura et al., 2014, Nall et al., 2015; but see Nexer et al., 2019 for low risk assessment). Interestingly, these structures may support local dominant biofouling species, such as the blue mussel *Mytilus edulis* in the North Sea (Coolen et al., 2020), to spread across soft sediment areas as IAS.

The IAS reaching the offshore structures may be transported to the site by support vessels (e.g., as shown by Nall et al. (2015)) and reach nearby ports by floating structures (Nall et al., 2022), cables (corridors), or local hydrography. Particular cables will function as biofouling IAS transport pathways in both directions like a two-way street. Thus, given the additional capability for expansion of the IAS colony by growth in any direction, **cables (and pipelines)** may be very successful **vector corridors** for IAS to new locations and regions. Particularly for interregional or intercontinental cables (data or power transfer), the cables are artificial dispersal corridors for the biofouling IAS and function as **pathways** and as vectors (for an example of subsea cable colonization, see Kogan et al., 2006). An unusual situation may exist with floating offshore structures (e.g., floating windfarm units); if anchorage at the seabed is lost, these change their function from stepping stones to a transport pathway for IAS and function as an interregional vector. If not found and brought to the original location, these units will drift freely with currents, possibly over far distances via oceanic gyres and tidal currents, while en route dispersing biofouling organisms posing a high risk to introduce IAS into new regions. If slowly wet-towed to a harbour, any equipment brought to port there is a high-risk vector for new IAS reaching the new stepping stones and the ecosystem (Iacarella et al., 2019; Nall et al., 2015, 2022).

Overall, offshore structures can provide settlement opportunities and serve as vectors for dispersal of biofouling IAS (see Tyrrell and Byers, 2007; Mineur et al., 2012; Airoldi et al., 2015; Sammarco et al., 2004; Ruiz et al., 2009; Miller et al., 2013; Adams et al., 2014; Nall et al., 2022).

vessel port of call. Here, the larval and free-living forms of the sessile IAS can be released and dispersed in the water column and set up home on any free space in the port. Not all larvae or algal propagules are potential IAS, nor will they all be successful, but as long as a few achieve reproductive stage, the potential IAS has made a significant step towards becoming an IAS. This new location (the port) is the first stepping stone for the IAS to reach the local community and expand their habitat. Usually more than one stepping stone is needed, particularly to establish an IAS population at a number of 'seed' locations. These 'stepping stones' (Boehlert and Gill, 2015; Shields et al., 2011; Adams et al., 2014; Bishop et al., 2017) can be other vessels visiting the port and calling in at other regional locations such as ports, marinas, and offshore structures, which have expanded rapidly recently (ocean sprawl: Firth et al., 2016; Bishop et al., 2017). Stepping stones may be visited by vectors such as ships with wide ranges, which can introduce the IAS from the stepping stone in one region to a different region. A vector can be any type of transfer mechanism (Ruiz and Carlton, 2003) and is not necessarily a ship. It may be any kind of mobile vehicle such as submersibles, ROV and AUV, but also structures being introduced into new regions such as pipelines, cables, or structures that are relocated and reach a new region where the IAS is not present as a native species.

There are hundreds of local, regional, national, and global websites that include information regarding NIS. Many are simple inventories, others are more comprehensive; however, few exist that specifically address marine environments. One of the most comprehensive web pages dealing with introduced species is the European Alien Species Information Network (EASIN), but it is not exclusively marine. Katsanevakis et al. (2012) described the development of this system which utilized >40 existing databases in an effort to provide integration and harmonization of information on alien species. The AquaNIS web page (Olenin et al., 2014; AquaNIS, 2015) includes a regimented system to include, store, and share data on IAS and is primarily European-focused. There are few specific websites maintained for marine invasive species. Two current examples include the relatively recently established World Register of Introduced Marine Species (WRiMS (see Appendix 1); Costello et al., 2021) which claims to be the most comprehensive standardized database of marine-introduced species, and that it forms the basis for a future global early warning system of marine introductions; and the National Estuarine and Marine Exotic Species Information System at the Smithsonian Environmental Research Center (NEMESIS), which is focused on the USA. The Marine Mediterranean Invasive Alien Species (MAMIAS) website is no longer active.

There is currently no solution to biofouling and IAS that works with 100% efficacy or that can remain active for over five years of deployment. Some of the biofouling species, (e.g., tunicates, mussels, anemones, polychaetes, and barnacles) are 'super' biofouling species and they cannot be eradicated in the receiving region. The super biofoulers are found around the world and were introduced to most harbours before biofouling science was initiated. In some instances, just one individual is enough to set up a new population as a result of asexual reproduction and fast, sessile, colonial growth. A more realistic means of preventing potential biofouling IAS from escaping their region of origin is the establishment of, and adherence to, very strict biofouling management plans and regulations.

In a survey of 100 shipping professionals conducted by Lloyd's List on behalf of a major coatings company, it was noted that the potentially catastrophic impact of biofouling on biodiversity through the spread of IAS was only recognized to be a significant risk by 14% of the respondents; 59% underestimated the negative environmental impacts of biofouling, and as many as 25% claimed to have little knowledge of the issue. One recommendation of the report was a united international approach to the issue (JOTUN, 2023).

This general lack of concern and understanding in a select, but prominent, group reinforces the need to engage maritime industries, including the newly developing Offshore Renewable Energy (ORE) efforts to become proactive rather than reactive in their approaches to issues concerning biofouling, biodiversity, and protection of environments.

2 Renewable energy generators (wind, tidal, wave, solar)

The quest for clean and renewable energy sources to replace fossil fuels and nuclear energy is a relatively new effort over the past three decades (Petersen and Malm, 2006; IPCC, 2016). Renewable energy generated from tidal, wave, sun, and wind resources as static and floating energy-generating options are rapidly growing industries globally (Boehlert and Gill, 2015), introducing new structures to the offshore environment, which are very different from offshore oil and gas platforms. Offshore wind energy had a value of US$33.52 billion in 2021 and is expected to grow at a compound annual growth rate (CAGR) of 12.1% to 2030 (https://www.polarismarketresearch.com/industry-analysis/offshore-wind-energy-market). These offshore structures are hugely diverse in form, materials, and function (Loxton et al., 2017; Figure 4) and if including essential component infrastructures, the situation can become overwhelming with regard to biofouling, IAS, and biofouling management. The recent appearance of these artificial structures associated with oil, gas, aquaculture, and renewable energy many kilometres offshore has provided vast new habitats for settlement of biofouling and IAS larvae and spores in deeper waters globally, including vertical biofouling zonation (see Figure 5). These offshore structures can provide settlement opportunities and may serve as stepping stones and vectors for dispersal for IAS (see Tyrrell and Byers, 2007; Mineur et al., 2012; Airoldi et al., 2015; Sammarco et al., 2004; Ruiz et al., 2009; Miller et al., 2013; Adams et al., 2014; Nall et al., 2022). It is important to consider that every structure deployed in offshore waters will face unique physical stresses and exposures to potential biofouling species, very different from structures close to shore, and expert designs will be needed if structures and equipment are to be reliable for periods of two to three decades (see Figure 4) for diversity of structures in the renewable energy field. For wave generators, Tiron et al. (2015) and Nall et al. (2017) (see Table 2) summarized potential stresses, noting differences in devices, effects of extreme wave events, accessibility for maintenance, and environmental considerations including biofouling. Overall, the impact of ORE on the natural marine environment is rather unknown and requires research (e.g., Soukissian et al., 2023; Methratta et al., 2023; ICES, 2024).

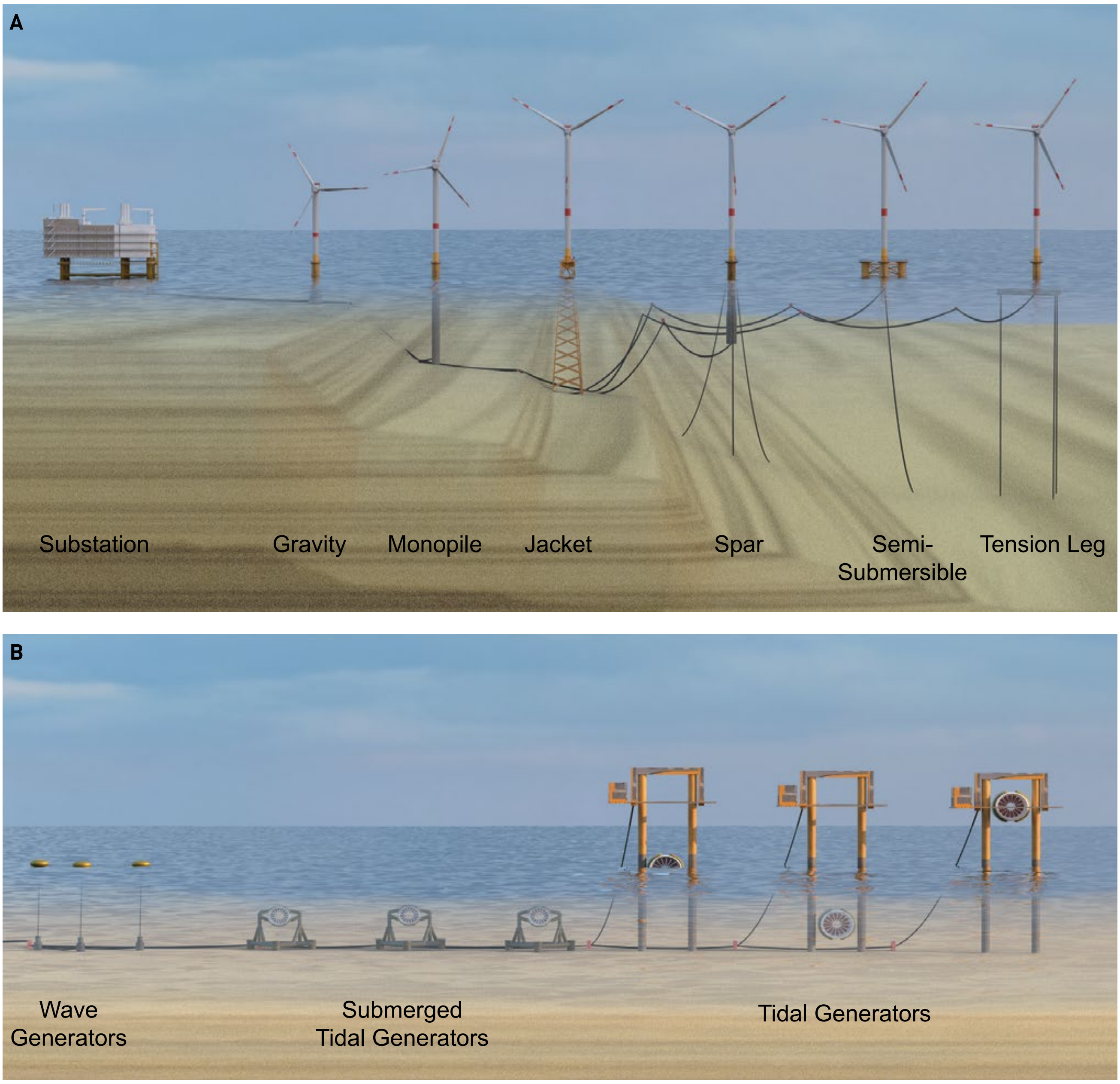


Figure 4. Generalized structures associated with offshore renewable energy generation; most systems are still under development.
Graphic: Eric Heupel

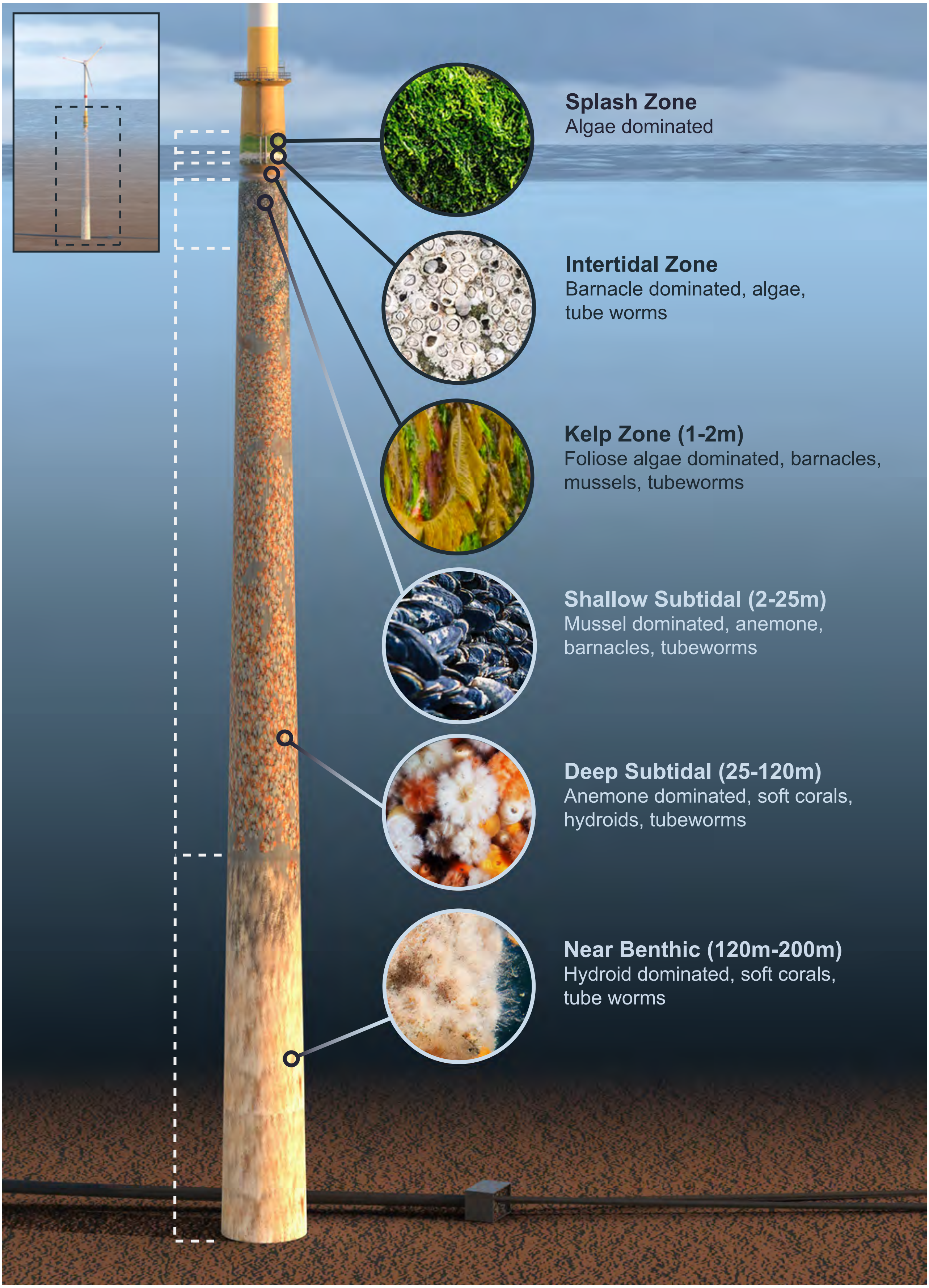


Figure 5. Schematic presentation of the biofouling zonation pattern and vertical distribution likely on offshore structures; not to scale.

Graphic: Eric Heupel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3

Wind energy generators

Engineering

Offshore windfarms were engineered and built during the past 20 years in Europe and are currently the dominant type of ORE generator worldwide (Figure 6). They are currently experiencing enormous expansion owing to their relatively easy installation compared to other ORE generators (Figures 7, 8; Box 3). More windfarms are in the planning phases worldwide (e.g., USA, Australia). Until now, standard windfarms were built in shallow water (the deepest pylon is currently at 58 m; SSE Renewables, 2022 a,b). Rotors are built on pylons made from steel, concrete, or a concrete base with a steel pylon (e.g., Canning, 2020), depending on the type of sediment and depth. Pylons (windfarm units) may form a lattice tower and even monopiles are not solid, but seawater filled. Thus, materials and forms are highly diverse and an ideal haven for biofouling species. Some structures, similar to those on terrestrial windfarms, may not be well adapted to the marine environment. Newly developed windfarms, not yet in operation, are the so-called floating windfarms. Here again, the underwater structures are surprisingly diverse, including anchorage and materials. Further plans for windfarms, beyond the generation of energy, include, for example, pairing them with aquaculture operations and using them as offshore ports. In particular, floating windfarms are considered for translocation as needed and for repair on land (ports). Windfarms are serviced by vessels often located in the nearest port or marina. Cleaning vessels operate on the windfarms daily to maintain ladders to reach rotors. Engineering support vessels visit structures, but are not necessarily stationed in the nearest port and may be flexible in their locations.

Specialized vessels set pylons, and rotors, and these vessels may be active regionally or interregionally, depending on the windfarm density. Every windfarm unit will have a cable to connect it with a central linking station serving many units. From that station, a subsea cable will allow connection to the shore and constitute the grid of the energy company. These cables will either be deployed within the sediment or protected by cable covers that encourage artificial reefs of biofouling (Figure 9). These scour protections for cables are demanded by the energy companies so that they can facilitate the perceived benefit of artificial reef formation.

Figure 6. Windfarm near Hilbre Island, United Kingdom.
Photo: Matthew Thomas, Wirral Council

Biofouling

Very few reports on biofouling at windfarms provide identification of specific biofouling species, and are limited in identification to mussels and barnacles. The true picture, however, is that the biofouling is very diverse after a few seasons (Figure 10; Appendix 2). Often the structures are first colonized by the local dominant species (e.g., hydroids, mussels) and the community will develop very fast, will develop very fast, within one season in temperate regions'. Most windfarms are currently operating in cold-temperate regions around the North Sea, English Channel, Irish Sea, and northeast Atlantic. Based on experience from aquaculture structures (Dürr and Watson, 2010), the expectation is that a biofouling community will be dominated within the first year by the blue mussel *Mytilus edulis*, ascidians such as *Ciona intestinalis,* and barnacle species, and later by kelp species such as *Laminaria* spp. and *Alaria esculenta* in the first 5 to 10 metres (e.g., DHI Water and Environment, 2005; Leonhard et al., 2006; Bouma and Lengkeek, 2009; Canning, 2020; Degraer et al., 2020; Figure 5). Deeper regions will slowly be colonized by, for example, anemones (e.g., *Metridium senile*). Some examples of biofouling IAS identified on windfarms were the barnacle *Austrominius modestus*, which is already naturalized in the region, the hydroid *Tubularia* (now *Ectopleura*) *larynx*, the Pacific oyster *Crassostrea gigas,* and the Atlantic slipper limpet *Crepidula fornicata* (Bouma and Lengkeek, 2009; Canning, 2020; Degraer et al., 2020). For more detailed information see Table 3 for IAS specifically identified on ORE structures.

Biofouling management

Interviews with relevant marine renewable energy companies indicated that there are very few **biofouling management plans** for windfarm structures in operation. Some companies include with their environmental impact assessment an outline invasive non-native species management plan which includes biofouling management generally (e.g., SSE Renewables, 2022a), whereby biofouling is not recognized as an issue for the ecosystem (e.g., SSE Renewables, 2022b). Nexer et al. (2019) recommend a management plan be in place for windfarms and that components for windfarms (e.g., foundations, floats) should not be stored in ports.

Overall, subsea areas of the structures are not treated with antifouling coatings, nor are they cleaned. It is unclear if the steel components receive an anticorrosion treatment. Discussions with industry representatives revealed that during the planning phase, and only in some countries, environmental surveys are conducted and evaluated by the environmental regulators. Past the planning phase, the aim and focus are on construction, not maintenance. There is apparently no requirement for a biofouling management plan per se by regulators in any of the countries with currently operating windfarms. While there are subsea surveys of the structures, these are technical engineering surveys, there are no biofouling or IAS surveys required, and, if surveys are done, they are to demonstrate the presence of an artificial reef. In fact, many windfarm companies seem to be unaware that biofouling or IAS may result in serious environmental issues. This may be the consequence of limited transparency

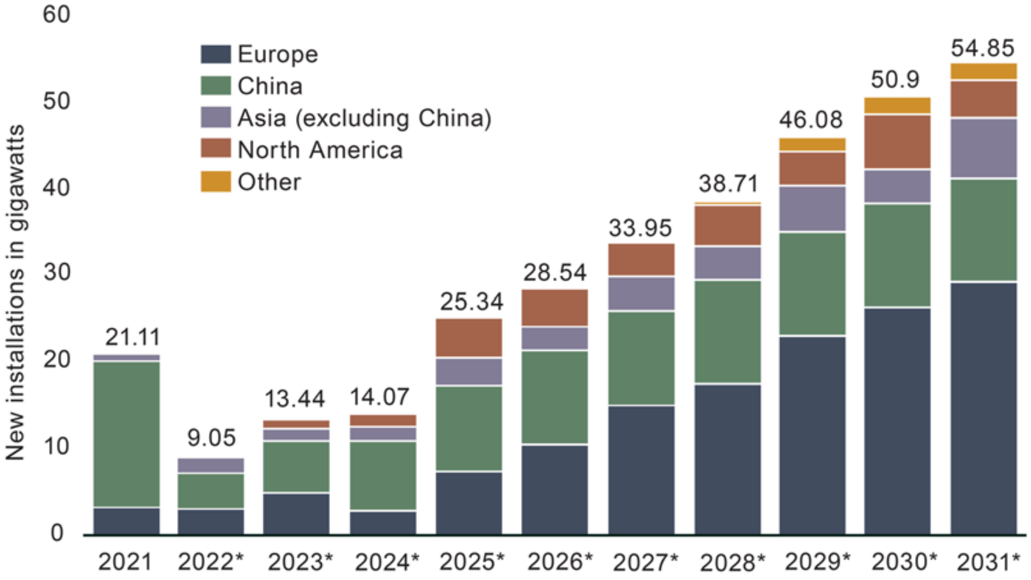

Figure 7. New wind installations forecast globally by region 2021–2031.
Source: Statistica (2023)

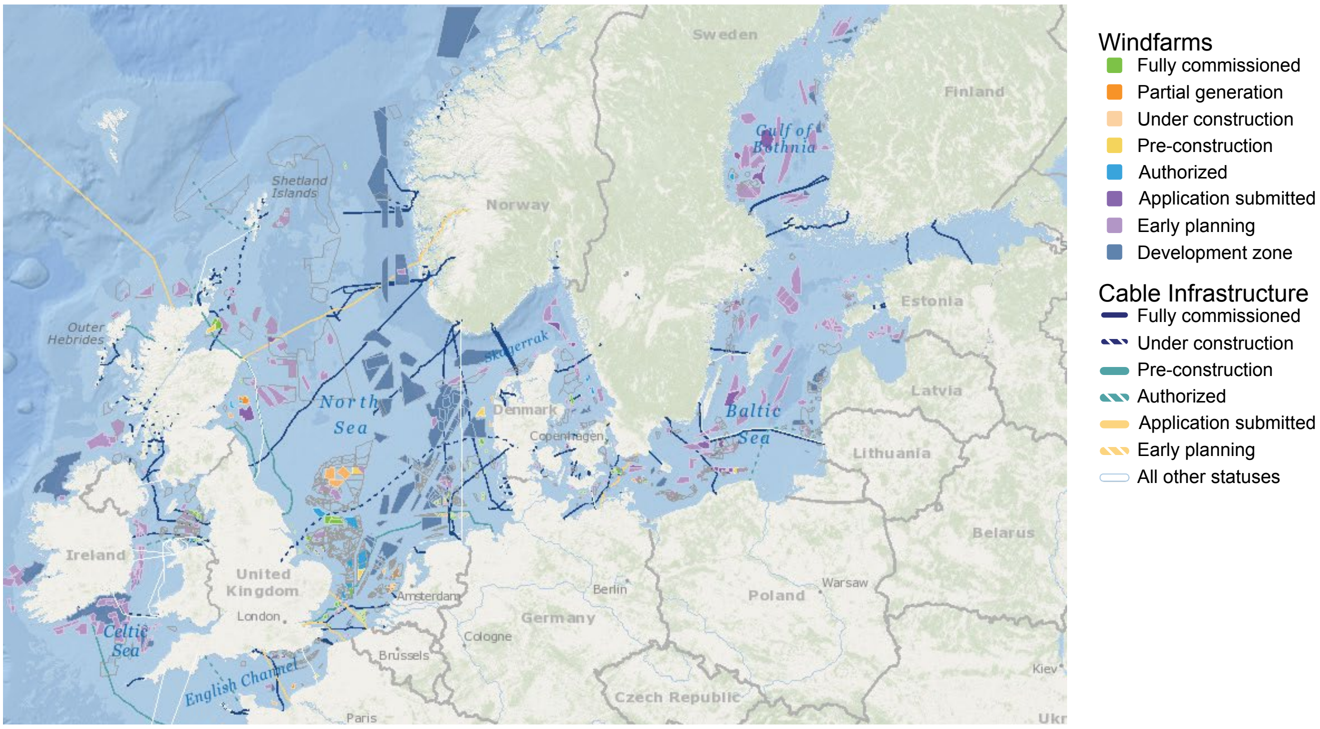

Figure 8. Map showing highly congested, complex and dense global offshore renewable energy operations in Europe.
Source: https://map.4coffshore.com/offshorewind

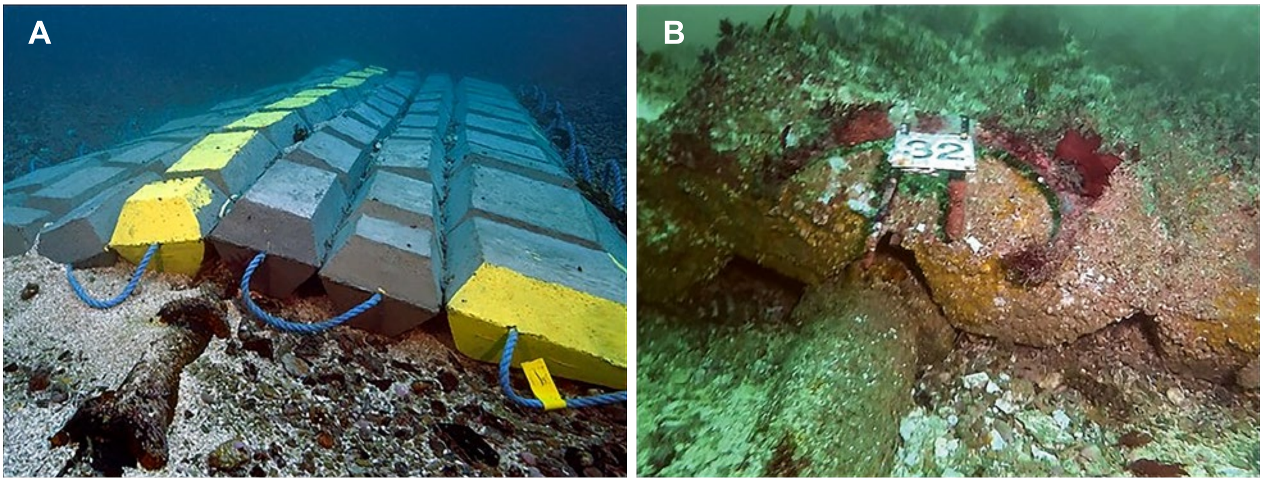

Figure 9. Iron shells and concrete mattresses of iron shells and concrete mattresses used to protect unburied cable at the Paimpol-Bréhat tidal turbine test site (France) (A) one month after installation; (B) six years later during a video survey.
Source: Hemery, 2000.

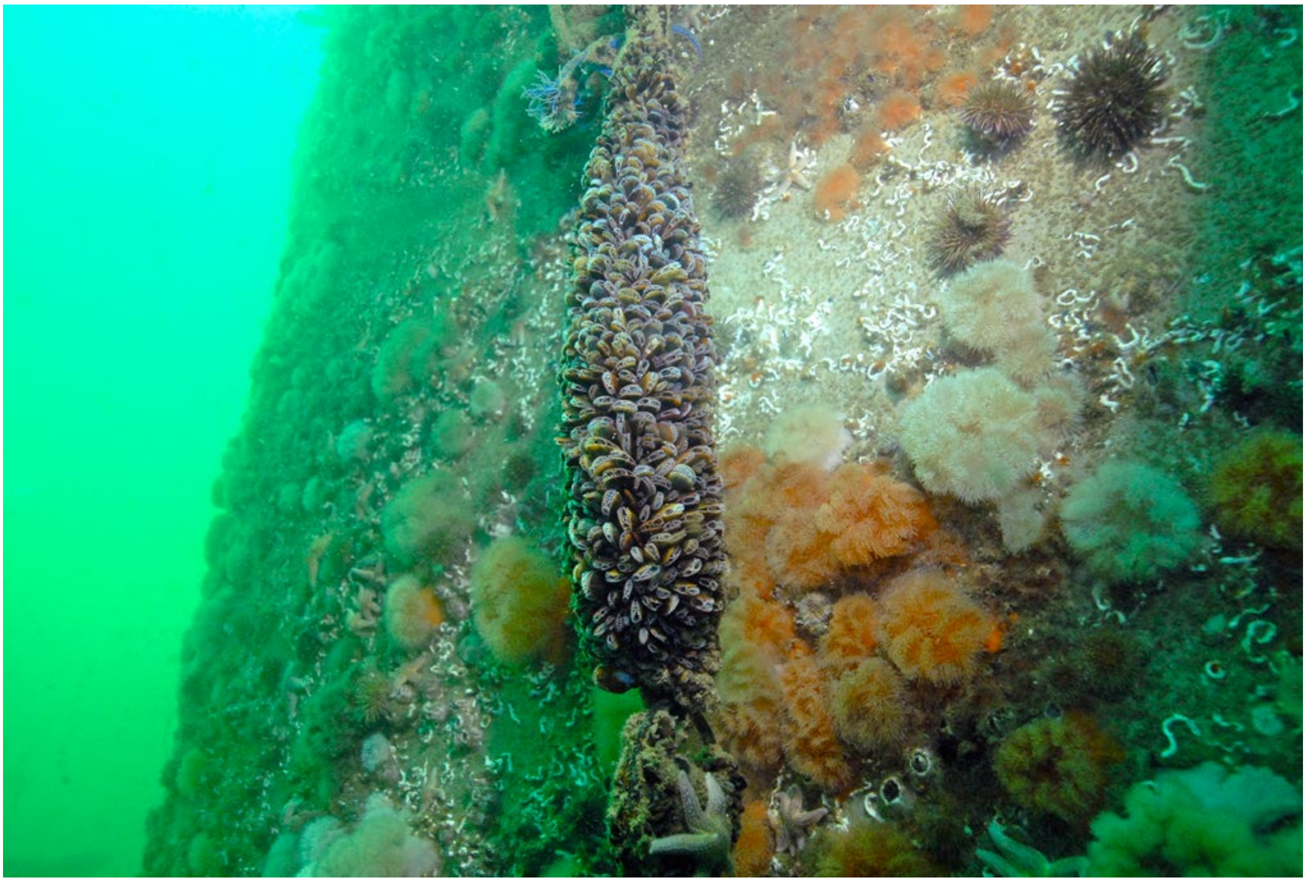

Figure 10. Hard biofouling community.
Source: Bob Rumes

BOX 3. Wind structure habitats

In order to help evaluate the significance of these structures as biofouling and IAS platforms, an attempt was made to quantify the new surface habitat area added to the water column. Very little has been published or reported quantifying the actual submerged surface area of any of these structures to date. This effort represents an initial attempt to fill this need, using average depths, diameters, and construction geometries. Installation, construction, and design variances in leg and strut diameters, geometries (e.g., jacket leg angle from turbine base to seafloor, use of multiple, smaller diameter parallel cross braces), and installation depths will cause the actual surface area created to deviate from these estimates.

Using the global output power densities analysis of offshore wind turbines from Enevoldsen and Jacobson (2021), currently operating offshore wind capacity represents 8,195.75 km^2 ocean surface area occupied. Announced projects reflect a further 15,319.45 km^2 ocean surface area utilized. Current installed offshore wind energy is concentrated in the European Union (51.0%) and Asia (48.9%). Announced projects, from permitting through construction phases, are primarily located in North America (41.2%) and the European Union (40.0%) regions, with a further 18.5% in Asia. Combined operational and announced offshore wind generation is mainly in European Union waters (43.7%), followed by Asia (28.8%) and North America (27.3%), with projects in the rest of the world making up 0.2%.

Table B1. Global installed and announced wind turbine support types

Turbine support type (see Fig. 8 for examples)	**Operating MW**	**Operating turbines**	**Global operational capacity (%)**	**Announced added MW**	**Estimated added turbines**	**Announced added global future capacity (%)**
Global all types	59 009	11 900		110 300	22 244	
Monopile, suction bucket	35 507	7 163	60.2	52 660	1 0620	47.7
Jacketed	6 152	1 243	10.4	16 244	3 276	14.7
Tripod	1 060	214	1.8			
Pile cap, multi-pile	5 415	1 092	9.2	1 057	214	1.0
Gravity base	816	165	1.4	5 230	1 055	4.7
Floating	154	31	0.3	35 109	7 081	31.8
Unreported	9 873	1 992	16.7			

Offshore wind generation and turbine numbers were obtained from the US Department of Energy (DOE) 2023 report. Turbine support types were only reported by total megawatts generated. All calculations are based on averages reported in the DOE report as well as data from 4C Offshore. Water column habitat area created for each structure type was calculated using average depths and diameters of main supports for each structure type (see Figure 8 for examples of common support structures). Jacket-type support structures were calculated with four main legs and cross braces of half the diameter of the legs. Note that this is the most conservative estimate, as the energy sector has successfully deployed jacket structures with up to 12 main legs and cross braces with diameters significantly larger than half the main leg diameters. Jacketed and Pile-cap structures were also evaluated with each leg or pile being perfectly vertical, when in actual installation they are always at an angle, which adds length and therefore surface area to both the individual legs and to the supporting cross brace structures. Gravity support bases were calculated using conic section tapering from the average reported base width to the average reported monopole section width over a height of one-third of the total water depth.

→

As so few floating turbines have been deployed as of this time, no calculations were made for these structures. It should be noted, however, that floating structures currently deployed or with design criteria available have substantial in-water structures (with drafts in excess of 20 m and displacements in excess of 20 m^3), along with extensive and often fairly thick anchoring systems. The VolturnUS-S semi-submerged reference platform system developed at the University of Maine (Allen et al., 2020) uses three catenary anchor chains of 0.185 m nominal diameter that can extend between 265 m and 850 m depending on needs of site location and water depths (60–200 m) (Pillai et al., 2022). While having a small diameter, even at their shortest, the anchor chains alone provide in excess of 924 m^2 of new surface area. Add in even an optimized hull structure of 20 m^3 displacement and the surface area added is at or in excess of 1,000 m^2.

Table B2. Water column surface habitat area added globally

Turbine support type (see Fig. 8 for examples)	**Average depth (m)**	**Average main support diameter (m)**	**Surface area/ turbine (m^2)**	**Installed global habitat added (km^2)**	**Announced global habitat added (km^2)**
Monopile	25	7	626.7	4.5	6.7
Jacketed	45	1.8	1 946.7	2.4	6.4
Tripod	35	7	1 378.2	0.3	0.0
Pile cap, multi-pile	45	1.8	2 076.5	2.3	0.4
Gravity Base	15	5	326.5	0.1	0.3
Floating					
Average per turbine			1 270.9		
Average per MW generated			161.4		
Total				9.5	13.8

Values for 'Announced' categories are based on current and historic values and do not account for continued improvements in per turbine power generation.

Source and analysis: Eric Heupel

or communication within the companies, as well as knowledge transfer externally, especially between industry representatives and scientists. The view taken by renewable energy companies seems to be a 'pro biofouling' opinion and an uninformed belief that the formation of artificial reefs is uniformly beneficial for the ecosystem. Artificial reefs on windfarm foundations were found to harbour a high number of IAS, they therefore became more dominant in the region with the windfarm expansion (De Mesel et al., 2015). Artificial reefs on offshore structures do not just induce stepping stones for IAS and their local and regional spread with the offshore ocean sprawl development, but they cause diversity loss in the ecosystem, jellyfish blooms, red tides, harbour pathogens, and unknown biofouling species (Schulze et al., 2020), interfere with and even counteract the conservation of ecosystems (Castro et al., 2021). Other researchers have taken the opposite general view that local diversity may increase, and have not considered the impact of IAS as well as local extinction of native species (Firth et al., 2016; Coolen et al., 2022).

Support vessels may require a biofouling management plan and record book as per shipping regulations (IMO Resolution MEPC.377(80) in 2023) and, therefore, will have applied antifouling coatings and, if required, will incorporate cleaning and ballast water treatment in their operations. These vessels will then pose only limited risk for IAS transfer due to mitigation of biofouling. Cables and ropes are not included under a biofouling management plan and yet can harbour extensive biofouling (see Figures 11, 12, 13). As cables reach long distances, the risk of transfer of IAS from origin (windfarm unit) to end and vice versa is high (see Box 2).

Best practice

There are no known biofouling management plan (BFMP) documents for windfarm structures. Best practices for support vessels include antifouling coatings, cleaning, and ballast water treatment as required by shipping regulations.

Consequences of unmanaged biofouling on windfarms

The lack of comprehensive biofouling management plans (and therefore enforcement of preventative measures) leads to biofouling communities on the windfarm structures as well as on cables and ropes, often referred to by industry as artificial reefs (Rivier et al., 2018; Raoux et al., 2017, 2019, 2021). The biofouling community on the windfarm structure will release algal propagules and larvae (Crisp, 1984) which will be carried to the next windfarm unit and will colonize these neighbouring structures with a similar community developing. Individual windfarm units are usually close enough together that re-seeding of structures can be achieved within a season, even after disturbances. The biofouling community on cables, ropes, and other structures are difficult to predict, particularly for long cable arrays of many kilometres (Bulleri and Airoldi, 2005; Sammarco et al., 2012; Bishop et al., 2017). Given that species can colonize this infrastructure over a wide local dispersal span and additionally expand their population on the cable by growth of the colony, the potential for long-distance exchange of species is high. Floating windfarms pose additional risks of IAS (see Nall et al., 2022) because of the added issue of potential failure of anchorage; the likelihood of such a risk is increased by biofouling load and storms. 'Escaped' floating windfarm units may drift with currents for long distances and their associated biofouling, and IAS may function as founder populations en route. This may mean that floating windfarms are not just stepping stones for IAS (Boehlert and Gill, 2015; Shields et al., 2011; Adams et al., 2014; Bishop et al., 2017), but also function as passive vectors.

Structural effects

The dominant species found on the windfarm structure described for cold-temperate regions in Europe are so-called 'heavy' species. On salmon aquaculture farms in Scotland, a 1-ton net can easily gain another 10 tons over the summer from mussel spatfall (Dürr and Watson, 2010). The same situation can be seen at the windfarm structures as the biofouling load multiplies exponentially, as the gravity foundation mass will increase, and that is to some extent a positive effect for the structure. The additional load will, however, very likely not be distributed evenly,

Figure 11. The ATOC/Pioneer Seamount cable (California, USA) in an unconsolidated sandy silt area showing three *Metridium farcimen* settled on the cable.
Source: Taormina et al., 2018.

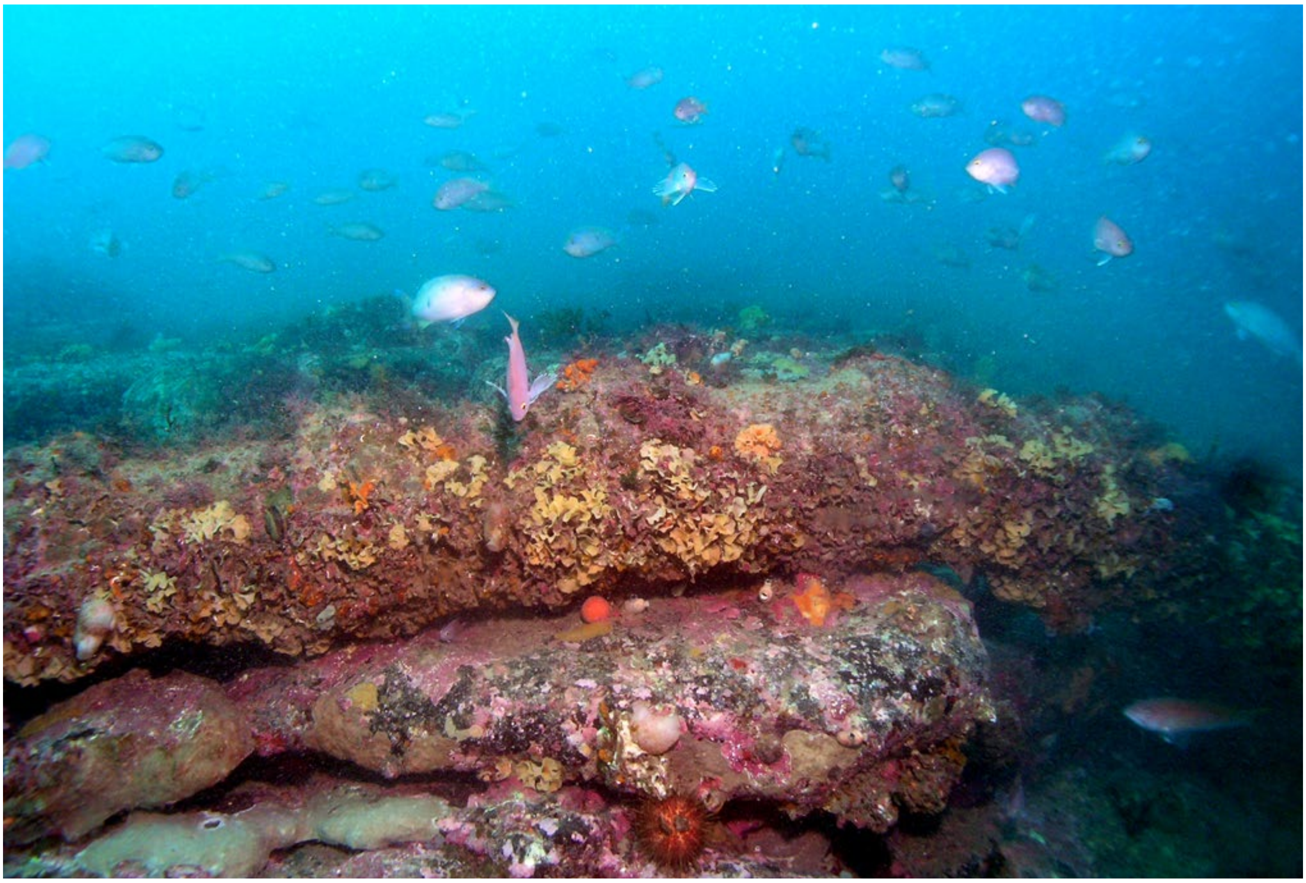

Figure 12. The BassLink cable (Tasmania, Australia), protected by a cast-iron half-shell, showing a heavy encrustation of algal and invertebrate species on the underlying basalt reef.

Source: Taormina et al., 2018.

as the species are filter-feeders and position themselves vertically to maximize exposure to food particles. This uneven weight load may compromise the gravity factor of the pylon in the sediment and stability, structural integrity, hydrodynamic inefficiency and may, in the worst-case scenario, lead to the failure and decommissioning of the unit (Jusoh and Wolfram 1996; Raoux et al., 2021; Schoefs et al., 2022).

Biofouling on the building materials for windfarm subsea structures, metal, and concrete, cause corrosion and erosion (Little and Lee, 2022). The biofouling species use species-specific arrays of adhesives to attach to a surface and often create cavities in the materials (e.g., barnacles). Biofouling facilitates the colonization of a microbiome that supports marine corrosion, (e.g., sulphate-reducing bacteria that cause anaerobic corrosion on metal). On concrete, the attached species erode the material which can lead to failure and to decommissioning of the structures with potential need of a re-build. Cable and rope materials may experience fatigue due to species adhesion, stretching caused by biofouling weight, or complete failure (e.g., Theophanatos and Wolfram, 1989; Jusoh and Wolfram, 1996; Det Norske Veritas, 2004, 2013, 2015, 2021; Murugan et al., 2020; Canning, 2020; Ren et al., 2021; Zhang et al., 2022; Maduka et al., 2023).

Environmental effects

Invasive aquatic species (IAS) are opportunistic and colonize artificial surfaces quickly and successfully (Brodin and Andersson 2009; Ruiz et al., 2009). Thus, it can be assumed that the biofouling communities on windfarm structures will include IAS components. Given the limited survey data on biofouling on these structures (e.g., DHI Water and Environment, 2005; Leonhard et al., 2006; Bouma and Lengkeek, 2009; Canning, 2020; Degraer et al., 2020; see Table 3 for more detailed information), there is little information available on species composition, dispersal dynamics between windfarm units, or origin of IAS. Focus is rather on an artificial reef effect (Rivier et al., 2018; Raoux et al., 2017, 2019, 2021). As the IAS release their planktonic algal propagules and larvae that disperse in flow, it is assumed that these will spread between windfarm units and potentially further distances from there. Thus, each unit (and each farm) is a potential stepping stone for IAS to relocate into the local ecosystem and change the composition, dynamics, structure, and instigate local diversity loss in that ecosystem (e.g., Apte et al., 2000; Floerl et al., 2009; Nall et al., 2015). Nexer et al. (2019) suggest that the stepping-stone effect for IAS at French windfarms is presently limited because of the low density of windfarms; this, however, may change in the future.

The IAS reaching the windfarm structures may be transported to the farm by support vessels (e.g., as shown by Nall et al., 2015 for floating structures and vessels, cables, or local hydrography from the port, and most likely combinations of these factors. Conversely, IAS will continue to spread by the same transport pathways that caused their initial transfer. Particular cables will function as biofouling and IAS transport pathways in both directions as a corridor (two-way street). As a result of the additional capability of expansion of the colony by growth in any direction by the sessile species, cables (and pipelines) may be very effective vectors for IAS to new locations and regions. An unusual situation may be expected with floating windfarm units if anchoring is lost at the seabed, as these drifting units become IAS vectors (IUCN, 2017). Drifting windfarms can transport IAS over very long distances while dispersing biofouling species and posing a high risk of introduction of IAS into new regions. If brought to a harbour (maintenance, decommissioning), there is a high risk of new IAS reaching the port (Nall et al., 2022).

Figure 13. Colonization of a cable deployed in a rocky environment of the SABELLA tidal test-site (France). A high density of kelp (*Laminaria hyperborea*) was observed on the naked cable.
Source: Taormina, 2019.


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4 Tidal and wave energy generators

Engineering

Tidal and wave energy generators have been in the early development phases for the last 15 years with several test sites in Europe. The tidal and wave devices are not typically deployed throughout the entire water column, with the exception of mooring structures and dynamic cables (Figure 14).

To date, none of the designs for tidal and wave generators are available commercially. Previously, very promising designs did not reach commercialization (e.g., Anderson, 2003; Nall et al., 2017). Worldwide, there are many areas where generators could harvest the energy driven by waves, tides, or currents. There are currently a number of designs in field tests. The current tidal energy generators are harvesting by propellers, some of the demonstrators are modular and may be used in tidal barrages in estuaries (see Figure 4 and https://www.emec.org.uk/marine-energy/tidal-devices/ for examples). Wave energy generators may be more diverse; some of the versions currently run as demonstration trials are working as hinged rafts (the movement of the hinges generates the energy). This general design and method has been used in earlier wave energy inventions (see for examples https://www.emec.org.uk/marine-energy/wave-devices/). Most of the current tidal and wave energy generators are situated at the sea surface, while a few types are deployed in the water column. All of these demonstrators are to be anchored on the seabed and will require subsea cables connected to link stations and main cables to the shore (for stresses on the structure, see Tiron et al., 2015).

Biofouling

The difference between the offshore oil, gas, and wind structures, and tidal and wave structures is that the former provide habitats for fouling organisms from the seafloor up into the water column. Cables also provide habitats for settling organisms (see Taormina et al., 2018).

Biofouling species colonizing tidal and wave structures are similar to species on windfarm structures, with the difference that the vertical zonation is less relevant (Appendix 2; Figures 15, 16, 17, 18; for biofouling on wave structures, see Figures 9, 13, 17). There are very few studies of biofouling accumulation on wave energy generators. Nall et al., (2017) reported 115 taxa, including four IAS. There were clear differences between depths, site and species composition between modules, and of the wave energy device. Another study reported the dominance of the blue mussel *Mytilus edulis* on wave energy generators (Langhamer et al., 2009) and the barnacle *Megabalanus rosa* on propellers (Katsuyama et al., 2014).

Biofouling assessments on tidal energy generators are equally sparse and fouling communities appear to be diverse (Want et al., 2017, 2021; see Table 3, Appendix 2).

Biofouling management

It is unknown if demonstration structures carry antifouling and anticorrosion coatings, if the industry considers biofouling management plans, or if there will be regulations for biofouling and IAS on the generators.

Figure 14. Open Hydro Centre Turbine at European Marine Energy Center (EMEC) tidal test site.
Source: https://www.emec.org.uk/; https://twitter.com/emec_ltd/status/955469431148343297.

It remains to be seen if biofouling management plans will be required for generators in operation and eventually by the regulator. Adherence to a comprehensive management plan is needed, not only after commercialization, but also during demonstration trials to avoid IAS transfer. Importantly, it is also unknown if the industry considers the organisms biofouling their structures to be potential IAS for other locations. Support vessels are required to have a biofouling management plan and record book as per shipping regulations when servicing the demonstrators and therefore will have applied antifouling coatings, cleaning, and ballast water treatment, as required. These vessels will then pose only limited risk for IAS transfer due to mitigation of antifouling if these precautions are in place. If devices have to be wet-towed to ports, however, this may result in a high risk for new IAS reaching the ecosystem (Iacarella et al., 2019; Nall et al., 2015, 2022; Figures 19, 20, 21). Cables and ropes are likely not under a biofouling management plan and will harbour biofouling. As cables reach extended distances, the risk of transfer of IAS from origin (generator unit) to end and vice versa is high (see Box 1, 2; Figures 1, 2, 3).

Unlike for windfarms, in the wave and tidal energy industry, materials and coatings are tested for corrosion and antifouling/foul-release efficacy at the potential site (Polagye and Thomson, 2010; Katsuyama et al., 2014; Want and Porter, 2018; Want et al., 2017, 2021; Linden et al., 2022). Husbandry (timing of settlement of fouling organisms), paired with cleaning, have been highlighted as important elements for both tidal and wave generators (Want and Porter, 2018; Want et al., 2017, 2018, 2021; Vinagre and Fonseca, 2022).

Best practice

Best practices in place (or not) are unknown, as all of these generators are in development phases and information is confidential; however, it should be noted that on some demonstrators, antifouling coatings were tested and a combination of husbandry (spatfall) with cleaning was suggested (Want and Porter, 2018; Want et al., 2017, 2018, 2021; Vinagre and Fonseca, 2022).

Consequences of unmanaged biofouling at the tidal or wave generators

For general information, see section on Windfarms.

Structural effects

With the high diversity in function, form, and materials of tidal and wave demonstrators, it is difficult to predict the structural effects of biofouling on a commercialized tidal or wave energy generator. Generally, biofouling may have impacts on loading of devices such as increased structural diameter, displacement volume, structural weight, mass, flow instability, and physical obstructions (see Jusoh and Wolfram, 1996; Schoefs et al., 2022). Nall et al., (2017) summarized some of the technical issues for wave energy generators (Table 2). Generally, the weight of biofouling on the floating generators in cold-temperate regions will be very high (Miller and Macleod, 2016) within a season (Dürr and Watson, 2010). That may lead to the generator slowly sinking and the generator may become dysfunctional. For hinged generators, like any movable section, the hinges may be very sensitive to corrosion resulting from biofouling and lead to malfunctioning. In the case of generators using propellers to produce energy, these will be very sensitive to biofouling and will be of great concern for the industry (Orme et al., 2001; Polagye and Thomson, 2010; Katsuyama et al., 2014; Walker et al., 2014; Miller and Macleod, 2016; Stringer and Polagye, 2020). A propeller with biofouling may stop completely or the efficacy of rotation will be decreased. The hydrodynamic response on wave-monitoring buoys may be dampened by biofouling (Want et al., 2018), though it might help to determine biofouling during operation. Langhamer et al. (2009) found no impact of biofouling on the response of the wave-generating buoys. Regarding general impacts on steel material, cables and ropes, and support vessels (see section on Windfarms), Miller and Macleod (2016) suggested that biofouling is an important knowledge gap for engineering decision-making, and that suggestion holds today.

Environmental effects

Please see section on Windfarms, regarding floating windfarms in particular.

There are some specific findings from the tidal and wave energy industry with regard to IAS risks. Biofouling IAS presence in harbours in northern Scotland was found to be positively associated with floating tidal and wave structure presence and their support vessel activity (Nall et al., 2015), and IAS were found at marinas and harbours close to test sites (Ryland et al., 2014; Loxton et al., 2017; Want et al., 2017). This suggests that the development of wave and tidal energy may have the potential to facilitate the invasion of IAS.

Figure 15. Two electrical connection hubs, one on top of the other, used at the wave test site of EMEC (Orkney, Scotland) and expanded view of barnacle colonization after three years at sea.

Source: Taormina, 2019.

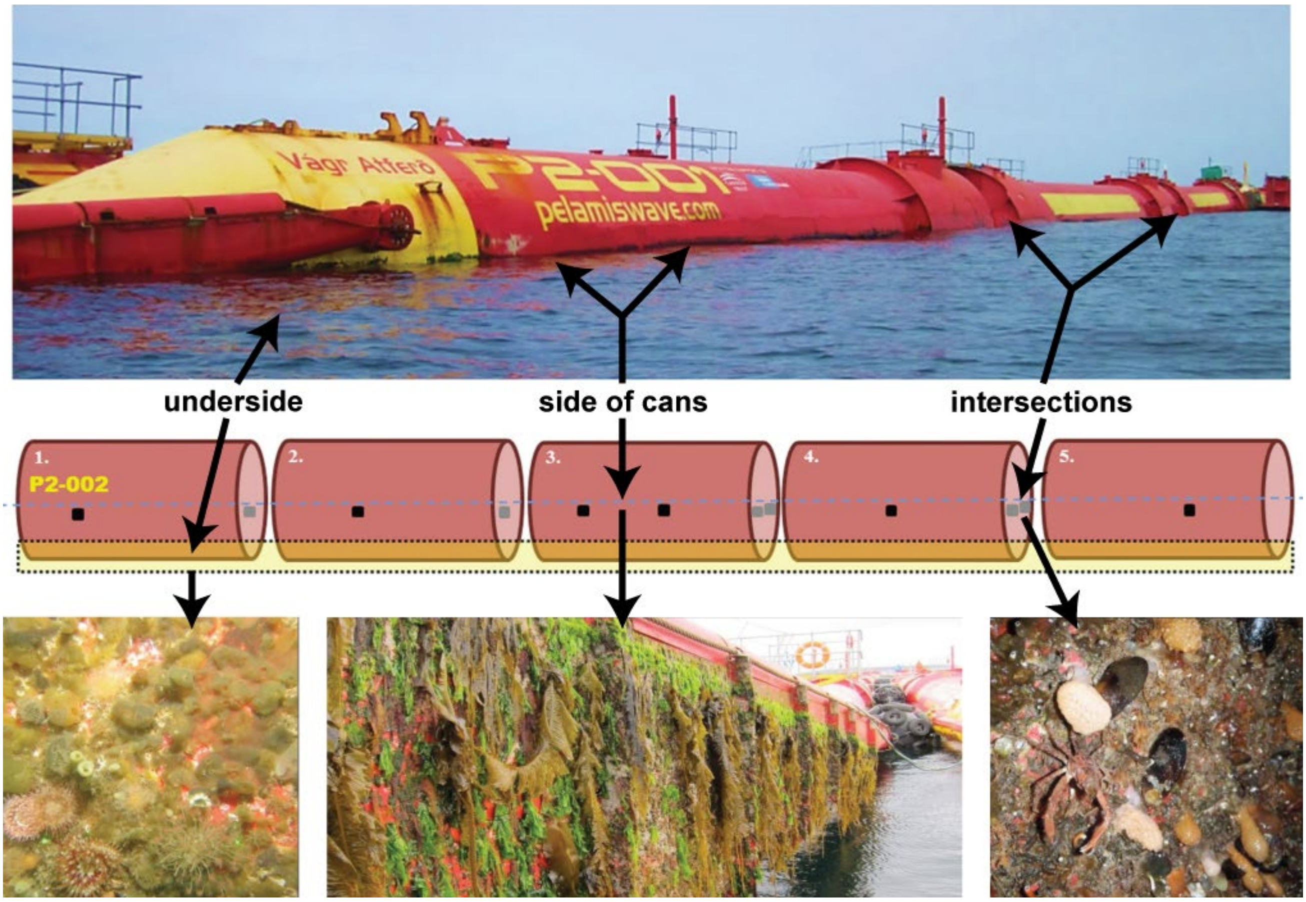


Figure 16. Biofouling sampling plan for the Pelamis wave energy converter (P2-002) and biofouling communities from sampling areas. (Lower left): Algal community biofouling sampled from the waterline of the P2-002 device; (Lower middle): Biofouling along the underside of the P2-002 device; (Lower right): Biofouling on the intersection of the P2-002 device at ~0.5-2.0 m water depth.

Source: Nall et al., 2017.

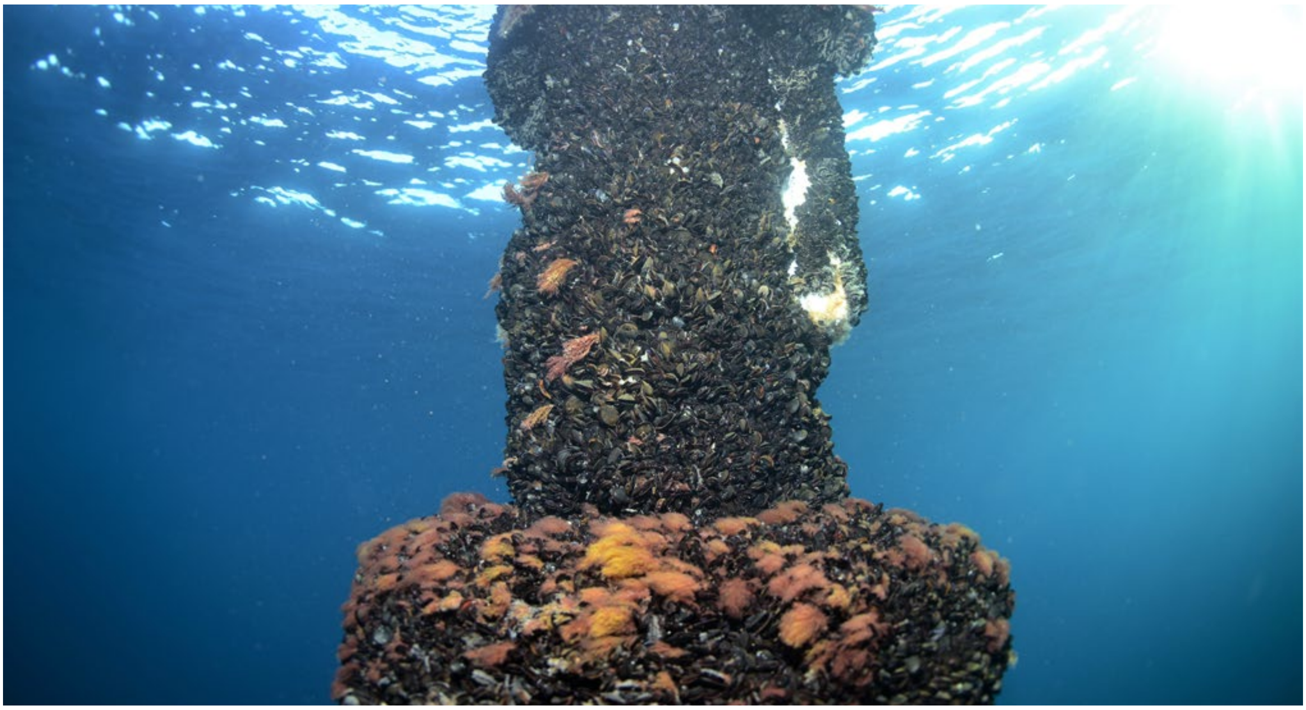


Figure 17. Floating ORE structure with biofouling community.

Photo: Nolwenn Quillien, France Energies Marine

Figure 18. A tidal current turbine colonized by kelp after three years of immersion at the Race Rocks site, Canada.
Source: Quillien et al., 2018.

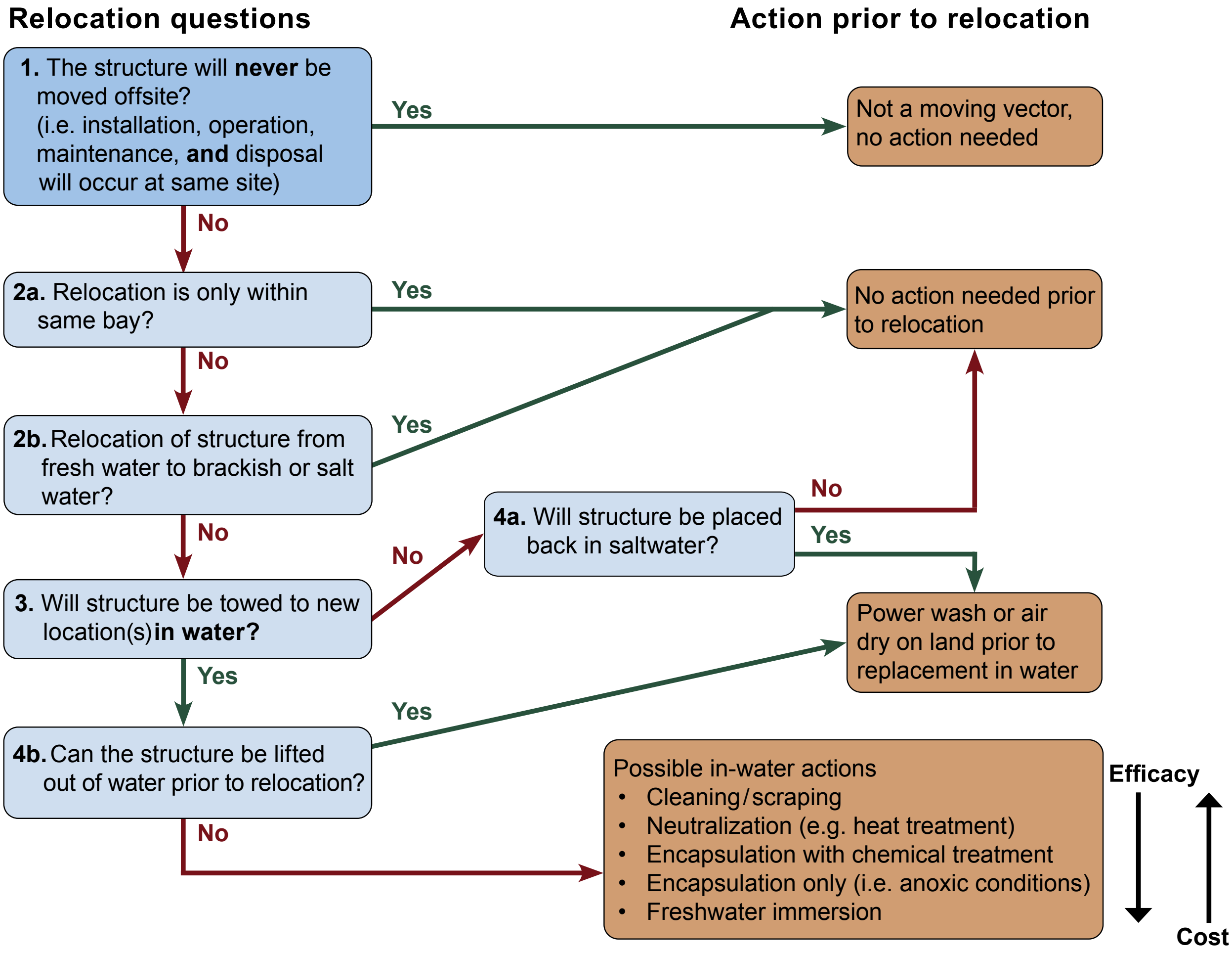
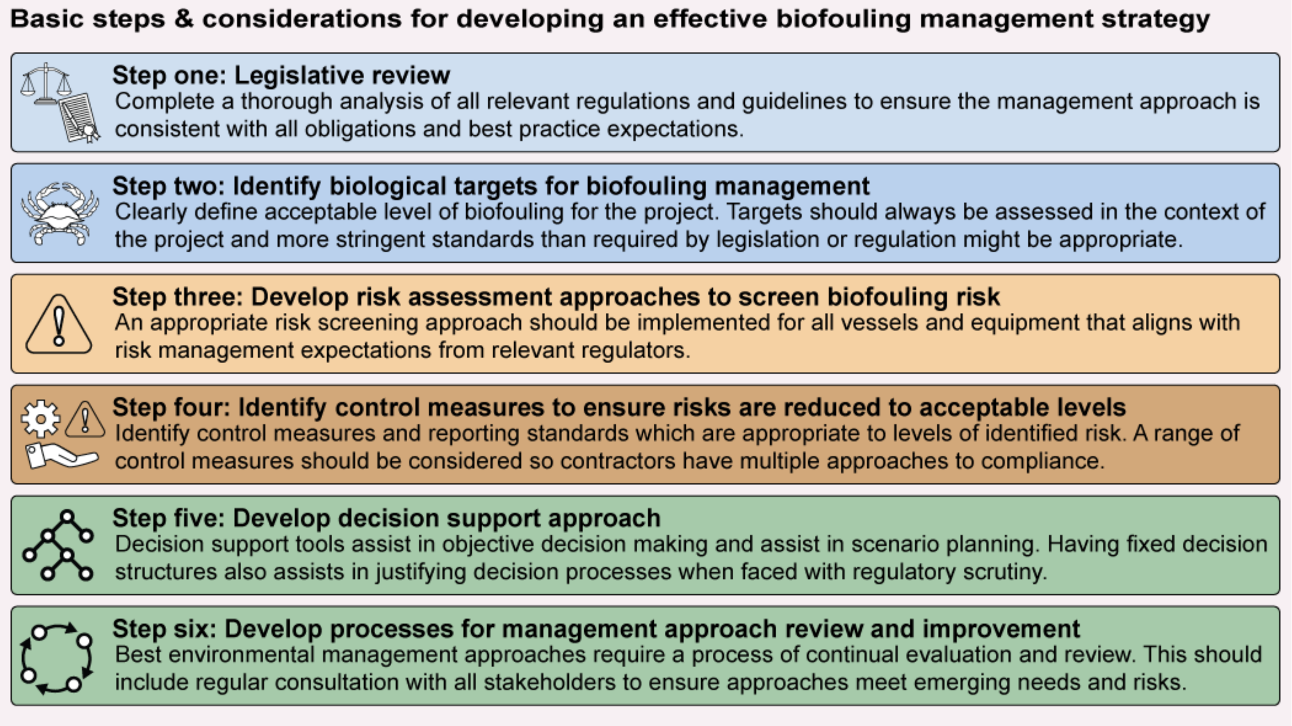


Figure 19. Conceptual framework for management of non-indigenous species spread through movement of static maritime structures. Actions to remove biofouling (yellow shaded boxes) effectively are based on survey answers to questions regarding the operation and movement characteristics of the structure (1–4, blue-green shaded boxes). Stationing in freshwater requires non-brackish water conditions and a sufficient amount of time to kill the biofouling.
Source: Iacarella et al., 2019.



Basic steps & considerations for developing an effective biofouling management strategy

Step one: Legislative review
Complete a thorough analysis of all relevant regulations and guidelines to ensure the management approach is consistent with all obligations and best practice expectations.

Step two: Identify biological targets for biofouling management
Clearly define acceptable level of biofouling for the project. Targets should always be assessed in the context of the project and more stringent standards than required by legislation or regulation might be appropriate.

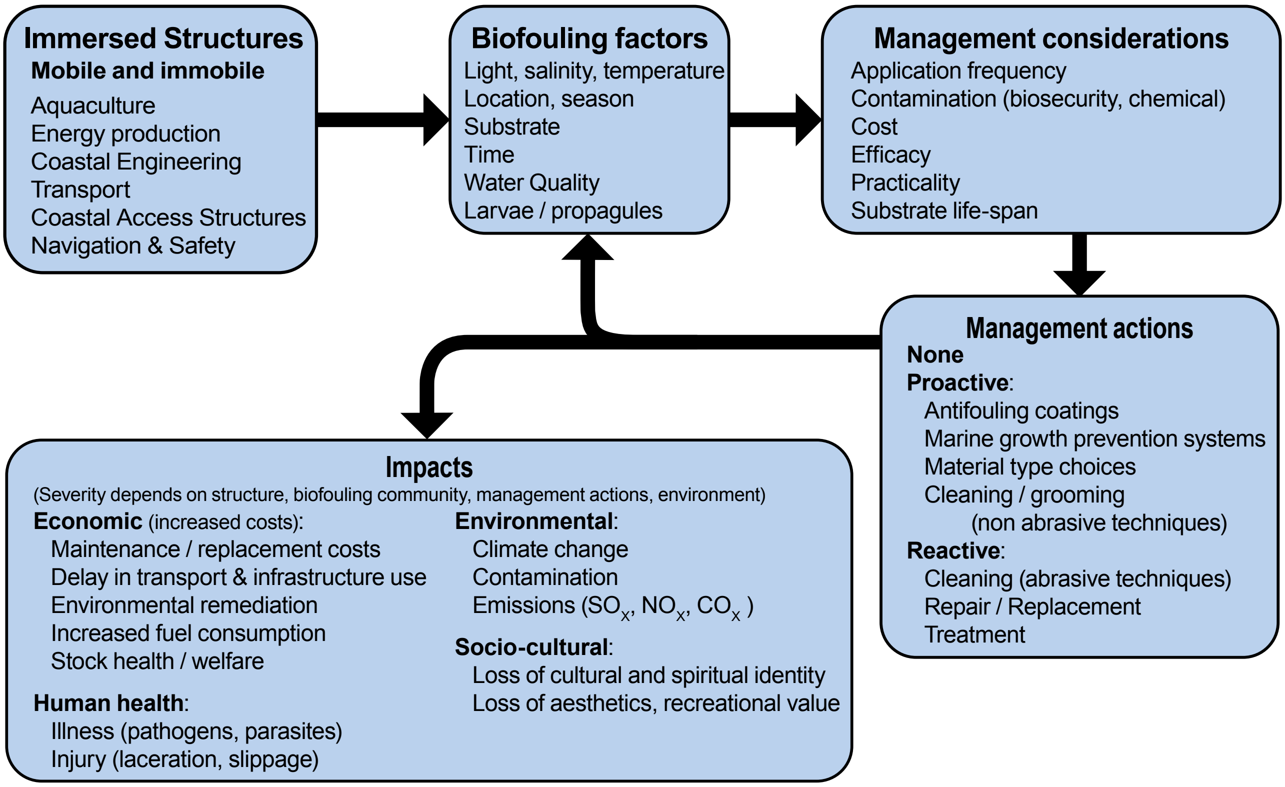
Step three: Develop risk assessment approaches to screen biofouling risk
An appropriate risk screening approach should be implemented for all vessels and equipment that aligns with risk management expectations from relevant regulators.

Step four: Identify control measures to ensure risks are reduced to acceptable levels
Identify control measures and reporting standards which are appropriate to levels of identified risk. A range of control measures should be considered so contractors have multiple approaches to compliance.

Step five: Develop decision support approach
Decision support tools assist in objective decision making and assist in scenario planning. Having fixed decision structures also assists in justifying decision processes when faced with regulatory scrutiny.

Step six: Develop processes for management approach review and improvement
Best environmental management approaches require a process of continual evaluation and review. This should include regular consultation with all stakeholders to ensure approaches meet emerging needs and risks.

Figure 20. Basic steps and considerations for the developing an effective project scale biofouling management strategy prior to locating platforms at offshore locations.
Source: IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships, 2024.



Immersed Structures
Mobile and immobile
Aquaculture
Energy production
Coastal Engineering
Transport
Coastal Access Structures
Navigation & Safety

Biofouling factors
Light, salinity, temperature
Location, season
Substrate
Time
Water Quality
Larvae / propagules

Management considerations
Application frequency
Contamination (biosecurity, chemical)
Cost
Efficacy
Practicality
Substrate life-span

Management actions
None
Proactive:
  Antifouling coatings
  Marine growth prevention systems
  Material type choices
  Cleaning / grooming
    (non abrasive techniques)
Reactive:
  Cleaning (abrasive techniques)
  Repair / Replacement
  Treatment

Impacts
(Severity depends on structure, biofouling community, management actions, environment)

Economic (increased costs):
  Maintenance / replacement costs
  Delay in transport & infrastructure use
  Environmental remediation
  Increased fuel consumption
  Stock health / welfare

Human health:
  Illness (pathogens, parasites)
  Injury (laceration, slippage)

Environmental:
  Climate change
  Contamination
  Emissions (SO_x, NO_x, CO_x)

Socio-cultural:
  Loss of cultural and spiritual identity
  Loss of aesthetics, recreational value

Figure 21. Impacts, influences and management considerations of marine biofouling on immersed structures.
Source: Demirel et al., 2022.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5

Solar

Engineering

Offshore energy generators using solar energy are currently in development by just a few companies (e.g., RWE). It is unclear if there are any demonstrators already in place in Europe or the USA. There are some plants in Asia (e.g., Singapore, China).

There is not much information available on the design of solar generators (Oliveira-Pinto and Stokkermans, 2020; Huang et al., 2023). It is assumed solar panels (photovoltaic) will be organized on floating rafts, similar to floating windfarm units that are anchored to the seabed and with cables feeding to a link station, and from there to the shore. Some of these solar generators may be associated with windfarms. Regarding floating structures, anchoring and cables, please see the engineering section for windfarms. Regarding the particular solar structures (see, for example, https://www.rwe.com/en/research-and-development/solar-energy-projects/offshore-solar/), these may be exposed to storms, waves, and sea spray. Solar panels may be susceptible to the impact of wind and waves, and to the corrosive effect of seawater and aerosols on metals and alloys. The effect of splashing may result in biofouling larvae and algal propagules carried onto the raft and the subsequent development of an intertidal community including IAS impacting the solar panels themselves. As there are no studies available, the risk cannot be assessed and research is needed urgently.

Biofouling management

There is probably no solar energy generator at a demonstrator TRL[5] available, and no information, but it is assumed that there is no biofouling management plan in place (and therefore no preventative practices being undertaken at regular intervals). Please see section on Biofouling Management of Windfarms for the biofouling Management of floating structures, support vessels, cables and ropes.

Best practice

Best practice documents are not available for the solar energy generators ,as they are too early in the development phase.

Please see section on Best practice for Windfarms. Best practice is only available for support vessels, see windfarms.

Consequences of unmanaged biofouling on solar energy generators

Structural Effects

Please see section on Structural Effects for floating windfarms, including support vessels, cables and ropes. In addition, biofouling may colonize in the intertidal zone of the solar panels and their base structures as larvae and algal spores may get washed up by splash and wave action. This may result in higher weight load, further corrosion of surfaces, as well as veiling or completely obscuring the photovoltaic units, thus decreasing their efficacy. These are assumptions; scientific field studies are needed urgently.

Environmental Effects

Please see section on Environmental effects of floating Windfarms including support vessels, cables and ropes. There is not enough known about these structures to determine additional environmental effects.

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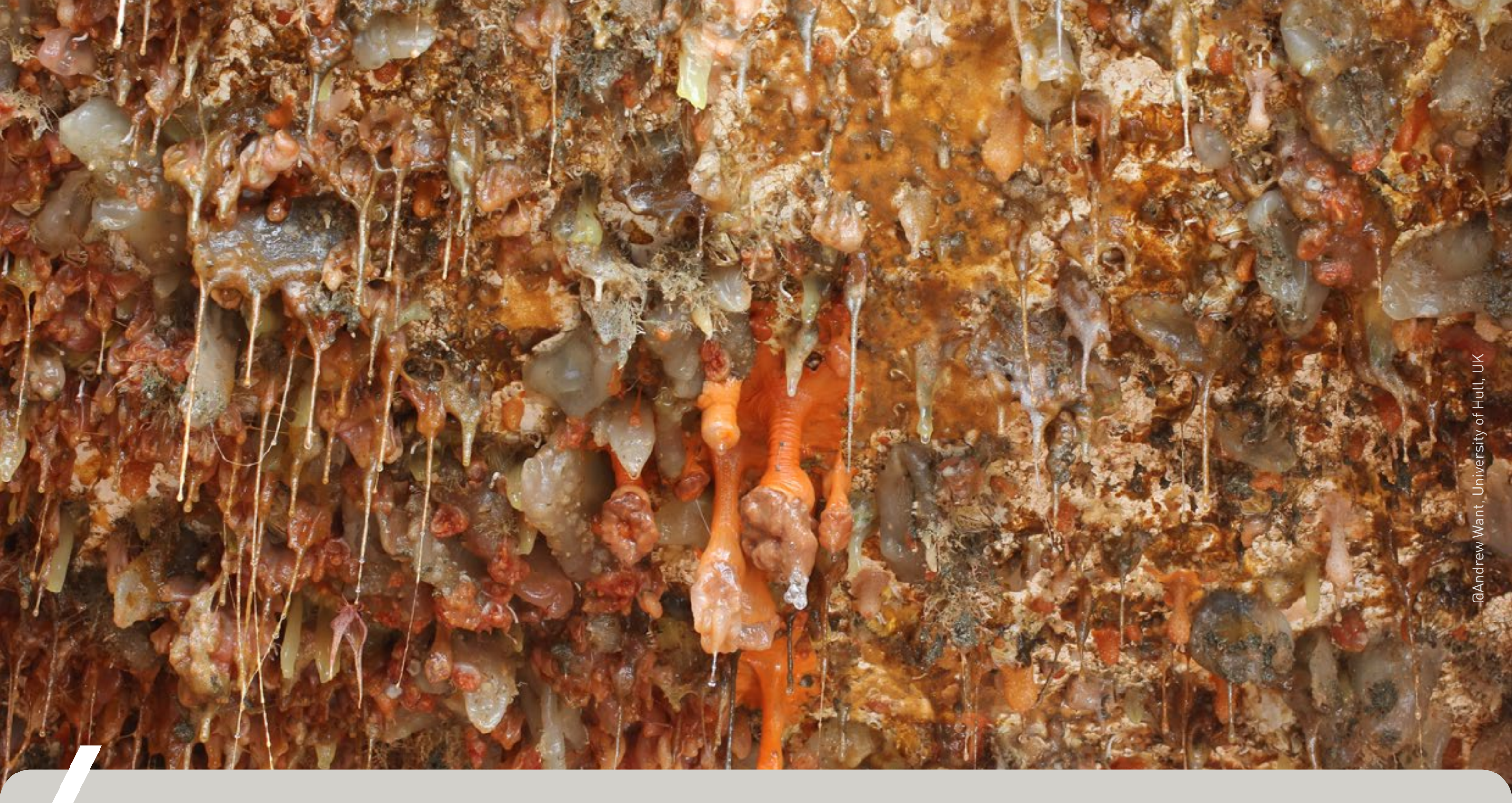
[5] *Technology readiness level*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6 Long-reach cables, pipes, and pipelines

Cables, pipes, and pipelines tend to be associated with structures; however, cables transferring data and energy can be isolated from structures. The telecom cables can reach from one continent to another (Figure 22). These structures are not new, yet research regarding biofouling and its impacts is lacking.

Engineering

Please see section on cables in the Engineering section for windfarms.

Biofouling

There is little literature or information available on biofouling on offshore cables, pipelines, or pipes, but see Figures 9, 11, 12, and 13 for examples. Cables, pipelines, and pipes can provide habitat for settling organisms, including extensive biofouling (e.g., Kogan et al., 2006; Taormina et al., 2018; Taormina, 2019). Kogan et al., (2006) showed that the anemone *Metridium farcimen* had recruited on an uncovered cable to a depth of 950 m.

An important point here is that these corridors will have to reach the surface at some point. IAS will be able to access that infrastructure mostly in shallow waters and utilize the corridor for further spread.

Biofouling management

Please see section on cables in the Biofouling Management section for windfarms. In terms of data or energy cables, these run mostly freely on the seabed, but are covered with a scour protection in places. There is no known biofouling management plan. As these structures are mostly running on the seabed, the International Seabed Authority (ISA) may need to consider development and implementation of biofouling and ISA regulations.

Best practice

Best practice documents are not available.

Consequences of unmanaged biofouling on cables, pipes, and pipelines

Structural Effects

The outer material of cables, pipes, and pipelines on the seabed may be deteriorated by the adhesive of the biofouling species or, in the case of metals or alloys, corroded. In the case of cables in the water column, these may suffer from increased temperature (conductor wire overheating), from drag, stretching or damage from biofouling weight and hydrodynamic loads, leading to failure of the cable (Paschen et al., 2014; Yang et al., 2017; Matine et al., 2019; Marty et al., 2021; Maksassi et al., 2022). Please see the section on Structural Effects on windfarms for further information.

Environmental effects

Please see section on Environmental effects of windfarms. In addition, the data and electricity cables connecting continents or regions become pathways for IAS between biogeographically different regions (see Box 2). Sherwood et al., (2016) found that the biofouling on the protective cast-iron half shell of the Bass Link is similar to the hard bottom community on which the cable is situated.

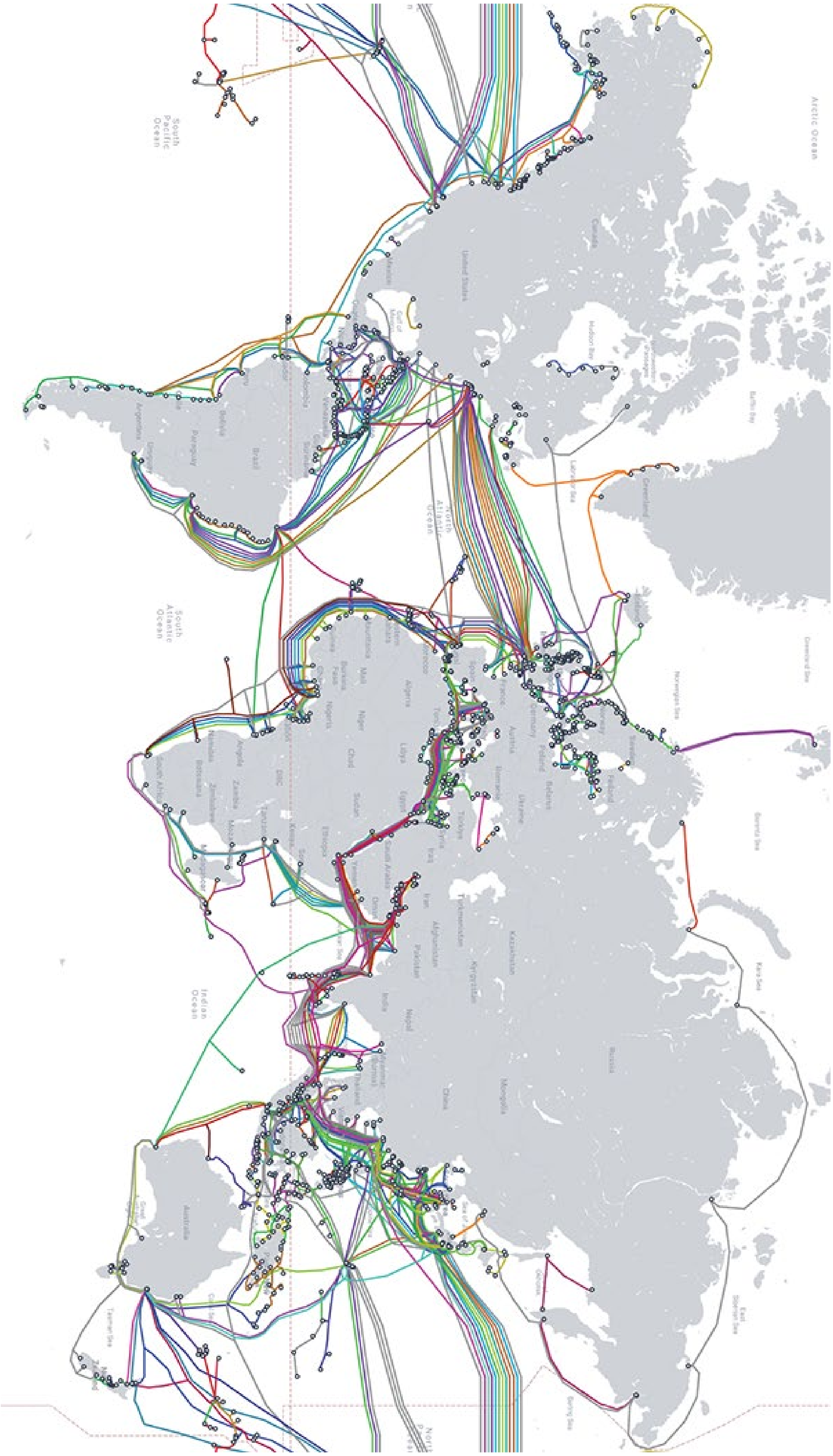

Figure 22. Map showing global deployment of submarine cables. Colours are mapped to the company and country that laid or runs them and cannot be delineate individually here.
Source: AquaComms TeleGeography; https://www.submarinecablempa.com.


© Nolwenn Quillien, France Energies Marine

7 Monitoring stations and buoys

Monitoring stations have been established worldwide for many years (Figure 23). They tend to have multiple users (often shared between countries) and uses, e.g.,, by government agencies, scientific institutes, companies, and for fields such as meteorology, physical oceanography, and biological oceanography. The stations consist of multiple arrays of sensors and other instruments from the surface to the deep sea and often in truly oceanic offshore conditions. Some stations consist of just one buoy. Stations are deployed worldwide and can be permanent or limited in time, e.g., two years in Antarctica. Stations are visited by different vessels (e.g., research vessels), often from different countries – clear potential vectors for biofouling and IAS.

Engineering

Arrays of sensors and instruments are set up individually or on platforms at different depths with buoys, floats and rafts on mooring lines, cables, and anchors (Figure 24). The deployment type can vary between stations, but the overall configuration is similar. Materials include metals, alloys, and plastics. Monitoring stations rarely lose anchorage, but parts of the arrays may get destroyed or ripped off in storms. Overall, the structures are well designed for high-sea oceanic conditions. Large buoys are usually deployed in shallower water (e.g., cautionary buoys and wave energy generators, see section on Tidal and wave energy generators).

Biofouling

Large buoys, such as cautionary buoys, in shallower water carry extensive biofouling included in the intertidal and splash zones (Figure 25). The biofouling community is similar in composition as described for wind, wave, and tidal energy generators.

Large oceanic monitoring stations may not often harbour heavy macrofouling species such as the blue mussel *Mytilus edulis*, but their biofouling is mostly limited to biofilm and dense mats of hydroids (Figure 26). As the monitoring stations carry a high number of specialized instruments and sensors, even these will be covered. This is true for deeper depths as well, as Zhang et al., (2015) report hydroids at a depth of 410 m. In this study, the barnacle *Lepas anatifera* was found between 15–30 m and the barnacle *Conchoderma hunteri* between 35–40 m. Meier et al. (2013) discovered biofilm on different materials exposed at 4,700 m depth. Interestingly, Bellou et al., (2012) demonstrated that biofilm communities developed differently on moorings in the Mediterranean Deep Sea depending on depth, orientation, and materials at 1,500 m, 2,500 m, 3,500 m, and 4,500 m.

Biofouling management

The monitoring stations as such seem to have no biofouling management regulations in place. Some of the sensors and instruments are treated with an antifouling coating,

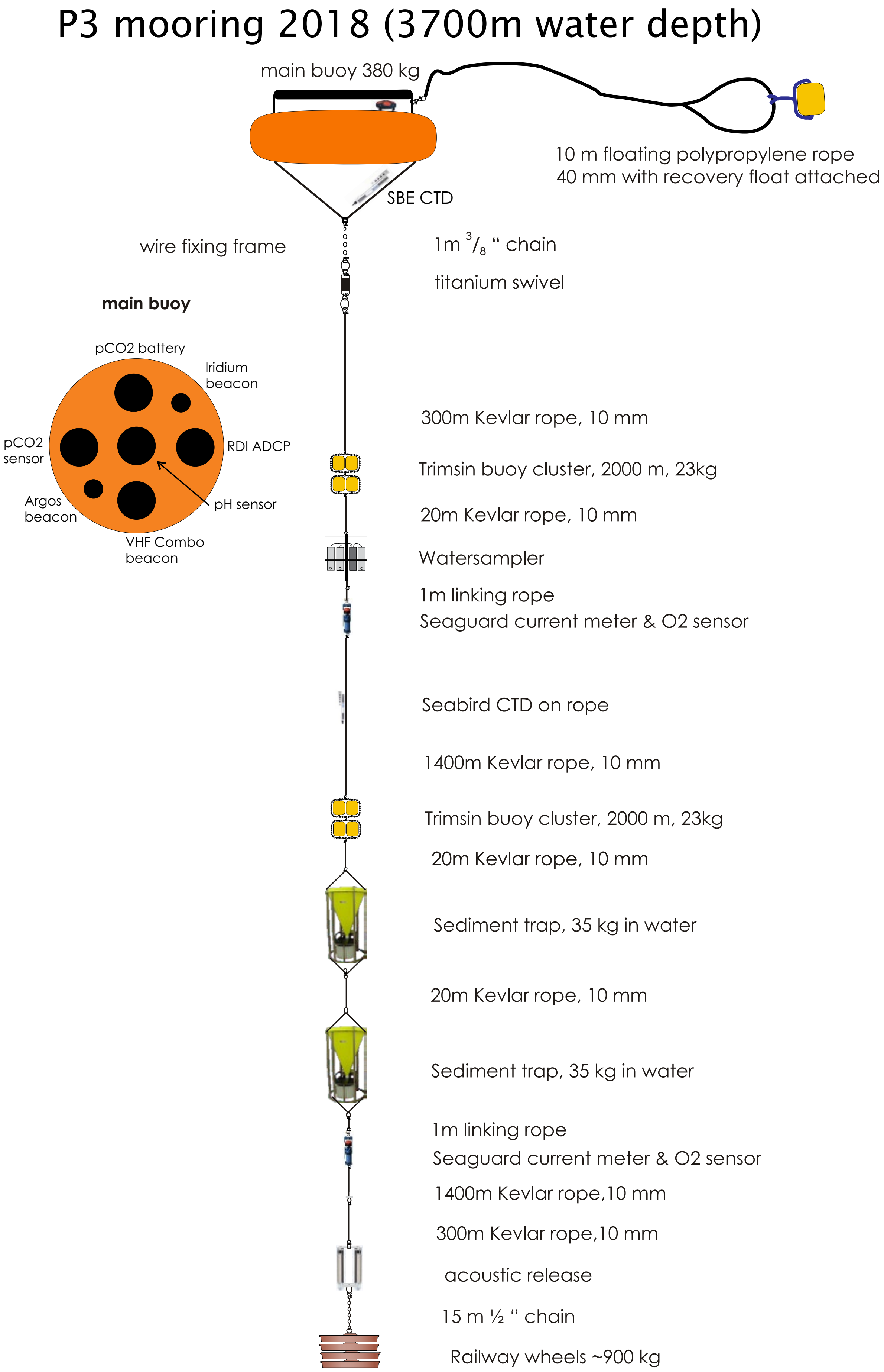

Figure 23. Array of P3 mooring buoy.
Photo: Peter Enderlein, British Antarctic Survey.

Figure 24. Photo of P3 mooring buoy deployment.
Photo: Peter Enderlein, British Antarctic Survey.

but often the sensor surface and housing cannot be treated as it would interfere with data quality. This loss of functionality of sensors is caused by the components of the coatings (e.g., metals). Meier et al. (2013) recommended consideration of mitigation measures for biofilm on sensors for deep sea deployments. Sensors, instruments, and parts of the monitoring array are cleaned by the visiting vessels in irregular intervals (Figure 26). Please see section on Biofouling Management of Windfarms, Tidal, and Wave Generators for the biofouling management of support vessels, cables, and ropes.

Best practice

Please see section on Best Practice for Antifouling of Floating Windfarms (best practice of support vessels, cables, and ropes). Best practice is only available for support vessels.

Consequences of unmanaged biofouling at monitoring stations

Structural effects

Depending on the location of the station, biofouling weight can be a problem. Stations in the high seas will not have a weight problem, but rather a problem as the sensors and instruments become defunct, with biofouling and biofilm leading to deterioration of data quality or complete loss of data. Decurey et al. (2020) recommend routine replacement of mooring lines on floating structures.

Environmental effects

Even with monitoring stations well distant from each other and without a routine schedule of visits by the same vessel, as opposed to visits by multiple vessels from different locations, there may be a risk of IAS transfer via visiting vessels. The monitoring stations may work to some degree as stepping stones, or a biofouled hub that can transfer IAS to other ports. This will depend on the geographic location of the monitoring station. When sensors and instruments are cleaned on board the visiting vessels, there may be a risk of transporting fragments to the next port. Additionally, with these vessels visiting multiple monitoring stations, biofouling residue from cleaning may reach even deeper arrays of the next mooring station and introduce shallow ecosystem IAS into a very sensitive and mostly unknown ecosystem.

Figure 25. Cautionary buoy with biofouling (dominant species include *Mytilus edulis*, *Semibalanus balanoides*, *Elminius modestus* (IAS), *Fucus serratus,* and *Ulva intestinalis*) in the Irish Sea.

Photo: Simone Dürr.

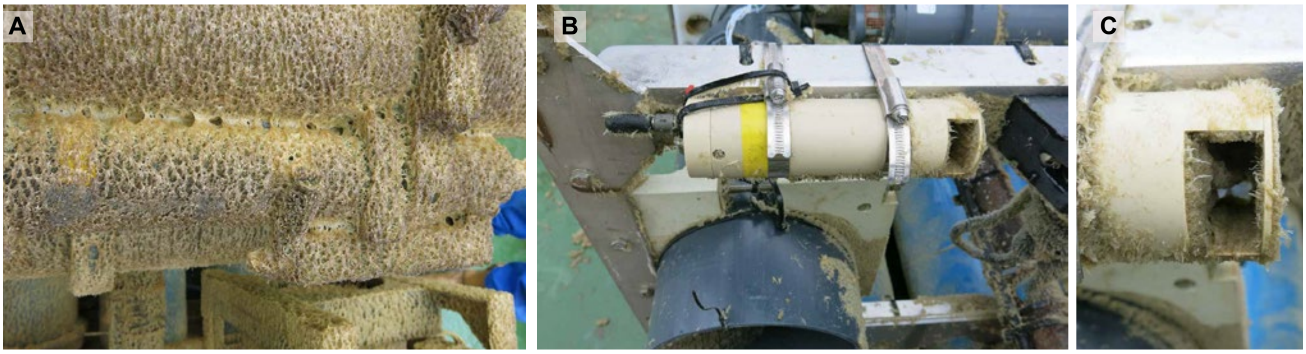

Figure 26. Biofouled high precision conductivity, temperature and dissolved oxygen (CT-DO) sensors before and after power-washing. Sensors were deployed on a frame suspended 30 m from a surface buoy at the Porcupine Abyssal Plain Observatory from one year (mid-2017 to mid-2018).

Photo: Jon Campbell.


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8 Offshore mining

Although marine mining has existed for decades, not much is known regarding biofouling in this industry. Resources mined include diamonds, phosphorite, rare earth elements, and polymetallic nodules, for example, off South Africa (Biccard et al., 2018) and in recent years, plans have been made by companies to further develop deep-sea mining, particularly for manganese nodules (Washburn et al., 2019; Durden et al., 2021); however, there is very little scientific literature and industry access has not been available.

Engineering

Mining operations offshore are currently using a number of different technologies, vehicles, vessels, and methods, for example crawlers (ROV), drill vessels, trailing suction hopper-dredges (TSHD), and ploughs (Biccard et al., 2018). Equipment such as crawlers is associated with one or two ships and support vessels, while other equipment is part of the actual vessel, such as the TSHD. Structural components are generally metal and polymers; the complexity of the designs make cleaning at sea challenging.

Deep-sea mining operations are still in their infancy and scientists currently assess potential operations for environmental risks; it is assumed that crawlers will be used in deep-sea mining. In their first deep-sea mining test, JOGMEC used a custom-built crust-excavator machine for cobalt mining in 2020 (Washburn et al., 2023a, but see also Washburn et al., 2023b).

Biofouling

Specific biofouling species are not known for shallower offshore mining. For deep-sea operations, biofilm will colonize the machinery and associated ROV and AUV.

Biofouling management

Ships and support vessels will be under biofouling management regulations; for more information, please see section on Windfarms. It is unclear if equipment such as drills, TSHD, ploughs, and ROV are under this legislation and require biofouling management. Seabed mining regulations are currently being developed by the International Seabed Authority (ISA) and the ISA is considering the inclusion of biofouling management regulations.

Best practice

Ships and support vessels will apply antifouling coatings and cleaning (in-water and dry dock; see Best Practice for Support Vessels at Windfarms, ROV, AUV, and cables). Any machinery or equipment is assumed to be cleaned, but when, where, and how are key. It is not assumed that the equipment carries antifouling technology.

Consequences of unmanaged biofouling in offshore mining

There is no peer-reviewed information available and these are deductions by the authors of this report.

Structural effects

For ships and support vessels, please see section on Windfarms. See also sections on ROV, AUV, and cables. Mining ROV and other equipment may be exposed to extensive corrosion conditions and their heterogeny of design, together with the surface damages, will result in rapid biofilm and macro biofouling and accelerate the corrosion process for material fatigue to the point of complete failure.

Environmental effects

Mining ships, support vessels, ROV, and other equipment are exposed to biofouling at the mining location, even if under biofouling management. Additionally, the mining location will change regularly. Thus, there may be different biofouling species appearing on the equipment and vessels. Vessels will need to move to ports and harbours regularly and will be stationary there as well. At this point, further biofouling may accumulate, resulting in a diverse community with potential IAS redundant. The vectors, vessels and ROV, may transfer (potential) IAS from different depths to different locations and even regions. In particular, the very delicate deep-sea ecosystems may be at risk as a result of the lack of IAS knowledge in this system, as was shown in recent studies at the Clarion Clipperton Zone in the Pacific (Washburn et al., 2019, 2021, 2023a,b; Durden et al., 2021; Williams et al., 2022).

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9

Mobile associated equipment and infrastructure (support vessels, remote operating vehicles (ROV), autonomous underwater vehicles (AUV))

This section is included as the role of support vessels is becoming increasingly important in ORE, oceanic monitoring, and mining, while ROV and AUV play a daily role in other industries as well as research. As such, their roles in IAS transfer need to be considered – the windfarm section discusses support vessels and the mining section specific ROV and AUV for seafloor machinery. In particular, new AUV technology including artificial intelligence (AI) programming may play an important role in all maritime industries with recent developments in batteries, and modern specialized ROV and AUV are able to work at any depth.

Engineering

Both ROV and AUV are very diverse in shape and function and it is not possible to discuss all of them. Typically, AUV are used for long-term missions over months with data collection periods underwater and periods at the sea surface to transfer data via satellite (e.g., NOC gliders). These types of AUV are built for reduced drag and efficiency and sensory equipment is designed not to hinder this. Older AUV and ROV are rather the opposite of these sleek endurance AUV and are still built for mining: most are built as a box with sensory protrusions and mostly without a hull. Additionally, ROV have an umbilical connection to a vessel. Materials used are metals, alloys, polymers, and composites. Metals may have had anticorrosive treatment.

Biofouling

Very limited published literature is available; however, a biofilm is to be expected to develop rapidly after deployment. For gliders, the presence of gooseneck barnacles *Pollicipes pollicipes* and other unidentified barnacles has been reported (Haldeman et al., 2016).

Biofouling management

ROV and AUV can be considered as vehicles or vessels, yet they may not be covered under shipping regulations (see section on Biofouling Management for Windfarms, Support Vessels, Mining; see also Figure 27 for a biofouling management decision pathway). If there is any biofouling management present, it is unclear beyond some cleaning after use. Biofouling management is considered for AUV gliders and antifouling coatings without impact on the glider are tested on the AUV itself, while seams are treated with zinc oxide creams and polyurethane tape (Haldeman et al., 2016). Additionally, long surface time and long dives in shallow water known to be rich in biofouling are avoided.

Best practice

Overall, the best practice may be cleaning for ROV and AUV, while users of specialist gliders should consider antifouling measures and husbandry (Haldeman et al., 2016). Best practice regarding biofouling control on these devices will depend on the structural materials and their properties.

Consequences of unmanaged biofouling in ROV and AUV

Structural effects

It is highly likely that all ROV and AUV will develop a biofilm when on a mission. Specifically, the umbilical connection of the ROV will be susceptible. Biofilm may also appear on the housings and the sensory equipment very rapidly. The biofilm may contribute to slow corrosion of these vehicles and may lead to sensor failure or low data quality. Over time, the biofouling will contribute to wear and tear of the vehicles. Long duration use of AUV, similar to submersibles, will expose them to macro biofouling depending on the locations, in particular resulting from the need to reach the surface to transfer data (Haldeman et al., 2016). The macro biofoulers may damage the hull due to adhesives, leading to failure of the sensors and instruments or the vehicle itself. Additionally, the increased drag with hull roughness may lead to shorter battery lifetime.

Environmental effects

Particularly on AUV, during the time of non-active movement, biofouling larvae and algal propagules will attach and may recruit on the hull or the sensors while the vehicle is transferring data at the surface or during shallow dives (Haldeman et al., 2016). Also, during missions, there may be stops in greater depths and further propagules will attach. During months-long missions, a biofouling community may develop on the hull or sensors. With long distances travelled by the AUV, IAS may be transported to other local areas or regions as a vector. The ROV may collect IAS in biofilm and become a vector.

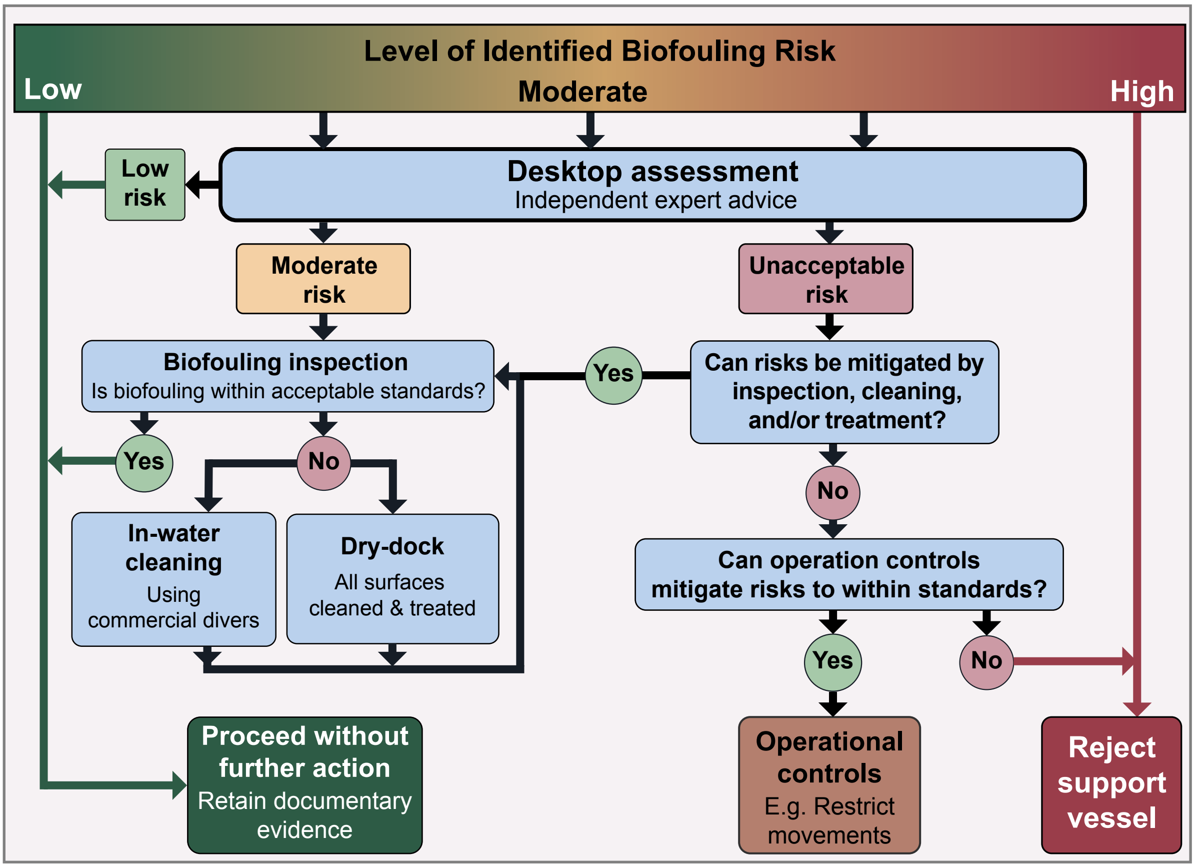

Figure 27. Generalized potential decision pathways to ensure responsible management of biofouling on support vessels. Appropriate control measures based on risk considerations should be determined for individual conditions. Biofouling inspection should be mandatory and desktop risk assessment should be mandatory for anything above a moderate risk. This example does not allocate particular actions based on specific risk categories (i.e., low risk/medium risk/ high risk) and titleholders should determine appropriate management pathways.
Source: IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships, 2024.


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Gaps and Recommendations

An overarching concern drawn from the information presented in this report is that there is currently limited recognition of the need for biofouling management and control of IAS in the offshore energy industries (see JOTUN, 2023). Given the global concerns highlighted by modern 'green' industry groups and the availability of advanced technologies, attention to these issues should be a routine consideration by the industries. The gaps identified regarding biofouling management and IAS are numerous. The offshore renewable energy industry focuses on build, not on maintenance and surveys, e.g.,, surveys in the dominant windfarm industry are technical engineering surveys only. There are no scheduled biological surveys on the structures focused on IAS because regulations for biofouling management, including biofouling IAS, are non-existent. In some instances, IAS are promoted on windfarm installations and the development of artificial reefs is seen as a bonus. Artificial reefs are generally brought forward by windfarm developers to support the image of an environmentally friendly industry at one end; at the other end, some regulators have not yet come to appreciate the existing background knowledge regarding the significant impacts of biofouling and IAS, thus some even pretend to establish industry structures as artificial reefs supporting another associated industry. One example is the link cables (e.g., for renewable energy generators) and their covers, which do not undergo biofouling management, but are praised as sources of diversity for the natural ecosystem (usually soft sediment) serving as an artificial reef. Thus, here hard bottom species are facilitated, i.e. biofouling species, which are mostly opportunists and are often IAS. Once settled on a cable cover (or pipeline), these species have free transport from one end of the 'two-way-street' vector, or corridor, to the other. Some of these reach the next continent via the deep sea, e.g., telecom cables. Biofouling species do not rely in this case on the dispersal of their propagules in the water column, but they are able to move on these corridors via growth forward, sideways, and backwards (asexual reproduction, mostly sessile species), part of the success story of biofouling and IAS. Covers of cables and pipelines may be rocks and rubble (often not local), but more and more specialized companies produce polymer covers, counteracting the anti-GCC strategy and promoting pollution (e.g., microplastics).

Regulations regarding biological issues are in place during the planning stage of new windfarms in some countries. In this case, the national regulator requires survey and/or biosecurity assessments before the next stage can progress. These surveys obviously do not include biofouling, as during planning there is no biofouling present on soft sediment at the location. After the windfarm is in operation, biofouling or IAS surveys are not required on the structure, nor is a biofouling management plan implemented while IAS risk assessments are in place. During the preparation of this report, no windfarm company that provided feedback acknowledged use of any antifouling technology or cleaning of the structures. There is no antifouling coating applied when the pylons are put in place on the seabed (wind farms in operation are currently within territorial waters). It appears that knowledge regarding biofouling, antifouling, and associated IAS is not transferred from other maritime industries to the newly emerging industries. This lack of knowledge exchange is perhaps fostered in these new industries by the speed of development of offshore infrastructures and market competition, while the country aims to generate more renewable energy cheaply and limit CO_2 output, i.e., present regulations may not be enforced for this industry, or needed law changes have not yet been applied in order to give the company the best start at low cost during the build and operation. But is this the case? Is this at the cost of the local ecosystem? Are these emerging maritime industries environmentally friendly? As discussed above, the issues of artificial biofouling reefs and the synergistic connection to IAS are clear; the result of this oversight on biofouling management is manifold and may result in increases in direct costs and other environmental impacts (e.g., diversity loss, ecosystem services or/and economic impact). Examples of points that need to be considered include:

1) Early decommissioning and re-build of the structure due to material fatigue, drag (storms), and corrosion facilitated by biofouling;

2) Facilitating the appearance of new IAS locally and regionally due to offshore structures (renewable energy generators, monitoring stations, stationary mining (particularly deep sea) equipment) evidently being stepping stones for invasive species brought there by mobile (support vessels, ROV/AUV) or static corridor vectors (pipelines, cables). Support vessels are already required to conform to biofouling management rules; no antifouling coatings have 100% efficacy for the duration of the five years to the next re-classification and dry-docking to re-apply antifouling, therefore. Local and regional support vessels may work as a stepping stone for the IAS to the static industry, while support vessels servicing via farther distances may be a vector transferring the IAS to a region.

Based on identified gaps presented here in biofouling management and IAS in renewable energy generators (wind, tidal, wave, solar), mining and deep-sea mining, subsea pipelines, cables and link stations, mobile vessels (including support vessels, ROV/AUV), as well as monitoring stations, a number of recommendations are presented, all representative of the urgent need for updates and development of new laws in relevant countries as well as for the high seas structures to protect ecosystems and citizens, all linked to the Sustainable Development Goals of Agenda 2030, particularly SDG 13 (Climate Action), SDG 14 (Life below water) and their inclusion in the United Nations Convention on the Law of the Sea (UNCLOS), Convention on Biological Diversity (CBD), and the Convention on Climate Change (UNFCCC). The industries addressed in this report are entwined with other industries presented in several GEF-UNDP-Glofouling publications and it is suggested to combine the recommendations for maritime industries into a unified guideline or convention for biofouling management and IAS. In this way, future new emerging technologies, structures, and industries will be covered by regulations for biofouling management and IAS to be adopted by Member States. Member States will then be confident in the type of regulations that are needed on a national level.

It is important to assemble comprehensive, on-line datasets of IAS redundant to inform management decisions, risk assessment, and prevention. Currently, these data sets are limited. While some data sets are available (see Appendix 1), they are not internationally comprehensive, nor are they peer-reviewed (see Marchini et al., 2015 for discussion). Further, they are often maintained by volunteers, are not uniform in their data management formats, and do not always provide detailed information/references regarding the source or veracity of the data included. Future efforts are encouraged to develop an international, comprehensive, rigorously reviewed data base that records alien species, i.e., not simply a list of species found.

There is a strong recommendation to improve transparency and reduce the amount of proprietary information within the industry regarding biofouling management and IAS. Industry structures, both static and mobile (if not already covered by shipping biofouling guidelines), must apply antifouling solutions (ideally environmentally friendly and biocide-free) including cleaning, while any artificial reef effect should be carefully considered. Any antifouling material or biofouling (including any IAS present) should not be released in a way that it accesses the seawater, in order to avoid pollution and IAS transfer. Biofouling and IAS monitoring is recommended to be conducted during the main biofouling season(s) and annually, at a minimum. Monitoring surveys should be carried out by independent agencies with biofouling and IAS specialists and using standardized survey methods set out by the regulator. Use and development of technology (e.g., AI) is encouraged for efficiency and proof of action, and to further increase efficiency, lists of target IAS should be developed and updated for local, regional and global levels with horizon scanning for potential new IAS by an independent international regulator. Static and mobile offshore structures should also be recognized by law to function as stepping stones, mobile transport, and corridor vectors.

Gaps

- Many global maritime industries underestimate the level of impact, both environmental and economic, resulting from biofouling, and biofouling is not a priority concern for the ORE industry at present. Consequently, there is often insufficient recognition and engagement by industry regarding the significance of IAS and biofouling, IAS transfer and establishment in the ecosystem, identification of species of concern, development of monitoring programmes, and associated issues to provide biofouling management.
- Some industries (e.g., solar, deep-sea mining) are early in their industrial development, so that biofouling management and IAS transfer are not yet routine parts of industry management plans in most offshore industries and countries of development.
- The magnitude of the role of ORE structures in the transfer and range expansion of IAS is unknown.
- There is limited acknowledgment and transparency by industries of the presence of invasive species and the synergistic relationship between biofouling and IAS on industrial structures, e.g., corrosion and material fatigue, as well as impacts on the ecosystem, e.g., local changes of dominant species, diversity loss, and invasive species transfer.
- Gaps remain regarding information available on the efficacy of antifouling coatings applied to ORE equipment.
- Greater relationships between industry and academia/scientists are required to study actual sites directly or know what information exists (or not).
- There is paucity of published information on biofouling and the ORE, and what is available is mainly focused on European efforts.
- Comprehensive, international, rigorously reviewed, and current databases concerning IAS and ORE marine environments are lacking.
- The role of ORE structures as stepping stones that promote the transfer and establishment of IAS could be further investigated, as few data exist to assist in assessments.
- Structural surveys are predominantly technical engineering surveys and greater improvements could be made in conducting biological assessments.
- Management of IAS is country-specific and thus development of international best management practices addressing biofouling and resulting IAS is difficult.
- Unified international regulations regarding biofouling, antifouling, and IAS for particular industries are lacking.

BOX 4. Benefits of proactive biofouling prevention

Overall, proactive prevention of biofouling provides positive impacts on social well-being and the economy of the maritime industry using offshore structures (excluding support and service vessels) for the following reasons:

- Engines, processors, and materials are less likely to fail
- Energy generation is more efficient
- Transport of electricity via cables and link stations is more efficient
- Data quality and collection are controlled and efficient
- Incidences of biosecurity issues resulting from IAS are fewer
- Incidence of IAS transfer into the natural local ecosystem is reduced contributing to sustainability and resilience
- Marine biodiversity of the local environment is protected

For consequences of biofouling on offshore structure, please see relevant sections.

Recommendations

- Detailed information pertaining to biofouling management and IAS, where it exists, should be made more freely available in order to assess IAS.
- Each energy generator, farm, vessel, and deep-sea mining structure, plus associated monitoring station, pipelines, and cables, should have a biofouling management plan (BMP) that specifically addresses biofouling and IAS impacts.
- All offshore structures and gear associated with ORE should also have a biofouling management plan to limit corrosion and subsequent early decommissioning of structures, as well as potential introduction of IAS.
- Biofouling management should carefully consider biofouling on structures and associates as artificial reefs, as they may have the potential to promote IAS establishment and ingression into the ecosystem.
- Biofouling management plans should identify suitable antifouling solutions for all structures.
- Annual biological surveys using standard monitoring protocols should be carried out by trained personnel with AI support to detect IAS ingression on offshore structures. Surveys should focus on IAS target lists (species currently in region; potential invaders).
- Gear and equipment should be designed in such a way as to reduce biofouling and to facilitate subsequent maintenance and the potential for harbouring and transferring IAS.
- Gear should be cleaned prior to transport to other regions; cleaning schedules should be judiciously determined taking into account larval presence and tidal currents; further research should be encouraged on models that can describe and predict these parameters.
- Survey methods and IAS databases could be established by international regulators who are also conducting horizon scanning for potential new IAS worldwide and their relevance for specific regions, offshore infrastructures, support vessels, and equipment (ships, AUV, energy generators, pipelines, cables).
- Research should be carried out to validate (or not) the stepping stone theory (connectivity) to provide data for development of BMP; funding should be made available to research efforts to monitor biofouling and IAS on ORE structures, to develop environmentally sound antifouling technologies and coatings, and to develop models that assess species transport and successful transfer between structures and throughout the water column.
- Connectivity, i.e., the stepping stone effect, should be taken into account in the planning of new installations.
- ORE structures and associated vessels and equipment should be recognized in regulations as having the potential to function as stepping stones, vectors, and corridors for IAS with biosecurity mechanisms in place to protect local and regional environments.
- Regulation of antifouling/biofouling control of infrastructure is needed to decrease incidence of IAS and material fatigue/corrosion (= longer lifetime of structure).
- Consideration should be given to suitable design of ORE structures and gear to withstand marine environmental challenges to encourage extended-term deployment counteracting the need of new build structures. This is especially pertinent as the industry is in the early stages of development.
- A standardized international IAS database should be considered that incorporates existing scattered IAS databases. This platform should be centrally maintained, international, and rigorously reviewed (however, decisions would need to be made as to the funding required to maintain it).
- Given the early stage of development of the ORE industries, special attention should be given to incorporation of biofouling prevention and management, IAS monitoring, and mitigations strategies as routine activities. Initial surveys of biofouling species present should be undertaken to establish baseline data.
- A unifying international treaty on biofouling for offshore industries including ORE, monitoring stations, mining, telecom and other users. Member States should address IAS transgression into ecosystems as well as pollution caused by inappropriate biofouling and IAS management.

Table 1. General techniques for preventing and removing biofouling in the marine environment.

Biofouling prevention strategies			
	Pros	Cons	Reference
Antifouling coatings (contains biocides, may be self-polishing)	Reduce overall fouling loads for 3-6 months; tin up to 5 years	Can be toxic to the environment; expensive, active ingredients accumulate in fish tissues settlement of all species (e.g., barnacles and hydroids) not always impacted. Some release microplastics	Brooks and Mahnken, 2003; Borg and Trombetta, 2010; Baldwin et al., 2011; Dafforn et al., 2011; Edwards et al., 2015
Copper alloy	Effective antifouling for up to 60 months; reduced frequency for cleaning; recyclable	Expensive; greater release of biocide (copper) over time than with coatings	Engel and Ray, 1985; Early et al., 2020
Foul-release coatings (mostly silicon- or fluoropolymer-based)	Easy to clean, environmentally friendly; minimize adhesion strength of fouling organisms; effective on hard foulers such as barnacles	Cleaning required and may damage coatings; short-term efficacy; does not work in static conditions; now includes biocides or hidden as catalysts; effective only at high speeds; little effect on biofilm layer	Terlizzi et al., 2001; Callow and Callow, 2006; Horner, 2019; Hodson et al., 2000; Hu et al., 2020
Tributylin (TBT)	Highly effective	Affects non-target organisms causing localized extinctions; currently banned in most regions (and by an IMO Convention) due to high toxicity	Minchin et al., 1987; Callow and Callow, 2006; Horner, 2019
Natural marine product (NMP) antifoulants used in antifouling coatings as biocides	Many choices of compounds (> 300 from one species); compounds can be mixed to increase antifouling potential	Organisms can overcome effects; bioaccumulation; often difficulties obtaining useable quantities of pure compounds; no evidence of long-term efficacy	Bobzin and Faulkner, 1992; Masuda et al., 1997; Steinberg et al., 1997; Armstrong et al., 2000; Flemming et al., 2000; Barbosa et al., 2007; Terlizzi et al., 2001; Hellio et al., 2009
Engineered microtopographical surfaces; microtexture techniques (PMDS, laser ablation, electro-polishing)	Reduces biofouling (mostly laboratory studies); limits cell settlement in biofilm in development stage; universal; no leaching into the environment; no harmful chemicals; ideal for niche areas; eco-friendly	Method in early stages of development; effective against algae and bacteria in laboratory trials; more research needed	Callow et al., 2002; Duncan et al., 2002; Bers and Wahl, 2004; Hoipkemeier-Wilson et al., 2004; Carman et al., 2006; Scardino et al., 2006; Chung et al., 2007; Schumacher et al., 2007a,b, 2008; Magin et al., 2010; Brzozowska et al., 2014; Rusen et al., 2014; Chen et al., 2015; Cunha et al., 2016; Sullivan and Regan, 2017; Wu et al., 2018; Sun et al., 2018; Horner, 2019
Ketamine (Medetomidine)/ Selektope	Available from paint companies; effectively hinders larval settlement; effective on hulls	Needs more data regarding potential toxicity	Dahlstrom et al., 2000; Holm, 2012; Lambert and Lambert, 2023; Rittschof, 2023

Acoustics/ Ultrasound	Nontoxic; potential inhibited barnacle settlement; reduced settlement with increased exposure time and acoustic pressure	Not selective, multiple species will be impacted by use; most data based on small-scale or laboratory studies; more research needed, especially regarding safe use and potential combination of technologies	Mori et al., 1969; Kitamura et al., 1995; Seth et al., 2010; Guo et al., 2011, 2013; Legg et al., 2015
Electric fields	Claims of high efficacy; environmentally-friendly; economically feasible	Still controversial; research on scaling issues and real-world applications still needed	Abou-Ghazala and Schoenbach, 2000; Trueba et al., 2015; Piyadasa et al., 2017; Hopkins et al., 2021a
Heat	Effective at various temperature/time combinations	Not effective against barnacles and oysters	Wotton et al., 2004; Piola and Hopkins, 2012; Cahill et al., 2019
Synergistic efforts	Coating based on contact inhibition, antifouling and fouling repellent all working together	Needs more data	Xie et al., 2020
ECOSPEED® (vinyl ester resin base, reinforced with glass platelets)	Environmentally-friendly; strong and lasting	Requires regular cleaning	Hydrex Group, 2011a,b
Air bubble streams	Reduce overall fouling loads, often dramatically	Difficult to employ on large scale; bubbles must flow continuously; delivery system itself may become fouled	Smith, 1946; Scardino et al., 2009; Bullard et al., 2010; Lowen et al., 2016; Hopkins et al., 2021b
Biological controls	Once released, can consume fouling species with little additional intervention	Obtaining enough biological control organisms can be difficult; not always effective	Valentine et al., 2007; Carman et al., 2009; Epelbaum et al., 2009; Atalah et al., 2014; Zhanhui et al., 2014; Sterling et al., 2016
Removal of biofouling			
Manual removal (e.g., mechanical scraping, brushing, power washing; divers, ROV; hydrodynamic cleaning/water jetting) Autonomous and remotely operated cleaning systems	Highly effective; hydrodynamic cleaning prevents coating damage; most coatings will be damaged if industrial pressure is used	Labour-intensive; required frequently; costly; can generate large amounts of waste material; some biofouling species survive high pressure treatment and fragments can survive and reattach; some species release larvae when stressed which can settled on newly-cleaned surfaces; will damage surface or coating; regulations needed; cleaning tools not durable for long-term use; high energy costs for complex application; long operational cycle; more data needed	Do, 1991; Minchin and Sides, 2006; Coutts and Forrest, 2007; Bullard et al., 2007; Paetzold and Davidson, 2010; Hopkins et al., 2010, 2011, 2021a; Morris and Carman, 2012; Reinhardt et al., 2012; Li et al., 2020

Air drying	Very effective	May not control all fouling organisms; does not remove calcareous shells or tubes; only applicable for structures and gear that can be removed from the water	Lutzen, 1999; Darbyson et al., 2009; Hillock and Costello, 2013; Hopkins et al., 2016
Spray-delivered chemicals	Some eco-friendly; low environmental persistence; can be used on variety of natural and artificial surfaces in and out of water	Some chemicals hazardous biocides; non-target, multiple species may be impacted; scaling can be an issue	Piola et al., 2010
Laser radiation	Effective on hulls; can be applied selectively; non-contact; can cover large areas	Need more data	Kostenko et al., 2019

Note: This table is not meant to be a comprehensive listing or assessment, but to present an overview of the myriad of methods available and their general level of application, with notations regarding research needs. Sources: Modified from Watson et al., (2009), Horner (2019), and Bullard et al., (2021), IOC-UNESCO, and GEF-UNDP-IMO Glofouling Partnerships (2024).

Table 2. Technical concerns for the wave energy industry associated with the accumulation of biofouling.

Category	**Technical concern**	**Reference**
Operation	Reduction in efficiency of energy extraction; decreased buoyancy of floating structures; inhibition of moving parts such as release mechanisms; blockage to water intakes; reduction in efficiency of heat exchangers	Orme et al., 2001; Tiron et al., 2013; Anderson, 2003; Renewable UK, 2014; Rajagopal and Jenner, 2012; Blair et al., 2014; Terlizzi and Faimali, 2010
Longevity/structural design	Increased hydrodynamic loads and drag as a result of increased diameter and surface roughness will provide added strain on structures; reduction of structural natural frequencies; increased structural weight	Jusoh and Wolfram, 1996; Yan and Yan, 2003; Shi et al., 2012; Fevåg, 2012; Anderson, 2003; Shi et al., 2012
Surface damage	Accelerated corrosion caused by microorganisms (e.g., sulphate reducing bacteria) that thrive in the anaerobic microhabitats beneath biofouling; physical damage to coating when biofouling removed	Beech et al., 2005; Australian Government, 2015
Maintenance	Increased drag leads to higher fuel consumption and time loss when towing devices; prevention of access to key areas during maintenance or monitoring, potentially concealing cracks or corrosion on the surface of the structure	WHOI, 1952; Schultz, 2007
Health and safety	Deterioration of maintenance access equipment (e.g., ladders or components to attach lifting equipment) due to biofouling may make them too unsafe to use	Renewable UK, 2014

Source: Nall et al., 2017.

Table 3. Species specifically noted as non-indigenous/invasive/exotic ORE structures.

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**Reference**
Algae					
Codium fragile ssp. *tomentosoides*	Dead man's fingers or felty fingers	Sessile	North Adriatic Sea	Breakwaters	Bulleri and Airoldi, 2005
Codium fragile ssp. *fragile*	Dead man's fingers or felty fingers	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod, 2013*
Dasysiponia (*Heterosiphonia*) *japonica*	Red algae	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod, 2013*
Ascidiacea					
Cnemidocarpa stolonifera		Sessile	New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010
Corella eumyota	Orange-tipped sea squirt	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod, 2013*
Didemnum perlucidum	White crust tunicate	Sessile			
Herdmania momus		Sessile	New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010
Bryozoa					
Bugula flabellata		Sessile	New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010
Schizoporella japonica		Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Watersipora subtorquata		Sessile	Santa Barbara Channel, California, USA	Oil platform	Page et al., 2006
Cnidaria					
Diadumene sp.	Anemone	Sessile	Santa Barbara Channel, California, USA	Oil platform	Page et al., 2006
Tubastraea coccinea	Orange cup coral	Sessile	Gulf of Mexico, Florida, USA	Oil platform	Page et al., 2006; Sheehy and Vik, 2010
		Sessile	Arraial do Cabo, Brazil	Oil platform	Ferreira et al., 2006
Crustacea (barnacles)					
Austrobalanus imperator		Sessile	New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010

Species	Common name	Mobile or sessile	Geographic location	Structure type	Reference
Austromegabalanus cylindricus		Sessile	New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010
Balanus perforatus		Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
Balanus reticulatus	Reticulated barnacle	Sessile	Belgian coast	Offshore buoy	Kerckhof et al., 2007
Balanus trigonus	Triangle barnacle	Sessile	Belgian coast	Offshore buoy	Kerckhof et al., 2007
Balanus variegatus		Sessile	Belgian coast	Offshore buoy	Kerckhof et al., 2007
Elminius (*Austrominius*) *modestus*	New Zealand barnacle	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2011
			Belgian coast	Offshore buoy	Kerckhof et al., 2007
			West/north coasts of Scotland	Navigational buoy	Macleod, 2013*
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Megabalanus coccopoma	Titan acorn barnacle	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2011
			Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Belgian coast	Offshore buoy	Kerckhof et al., 2007
			New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010
			Arraial do Cabo, Brazil	Oil platform	Ferreira et al., 2006
Megabalanus tintinnabulum	Acorn barnacle	Sessile	Belgian coast	Offshore buoy	Kerckhof et al., 2007
Crustacea					
Caprella mutica	Skeleton shrimp	Mobile	Billia Croo Orkney, Scotland	Wave energy converter	Nall et al., 2017
			Belgian coast	Offshore buoy	Kerckhof et al., 2007
			Santa Barbara Channel, California, USA	Oil platform	Page et al., 2006
			west/north coasts of Scotland	Navigational buoy	Macleod, 2013*
Charibdis hellerii	Indo-Pacific swimming crab or spiny hands	Mobile	Arraial do Cabo, Brazil	Oil platform	Ferreira et al., 2006
Hemigrapsus sanguineus	Japanese shore crab or Asian shore crab	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
Jassa mamorata	Tube-dwelling amphipod	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
			North Sea	Offshore wind farm	Leonhard et al., 2006

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**Reference**
Echinodermata					
Ophiocoma paucigranulata	Brittle star	Mobile	Arraial do Cabo, Brazil	Oil platform	Ferreira et al., 2006
Insecta					
Telmatogeton japonicus	Giant midge	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2011
			Belgian coast	Offshore buoy	Kerckhof et al., 2007
			Kalmar Strait, Baltic Sea, Sweden	Offshore wind farm	Brodin and Andersson, 2009
			North Sea	Offshore wind farm	Leonhard et al., 2006
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Mollusca					
Aulacomya atra	Magellan mussel or the ribbed mussel	Sessile	New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010
Crassostrea gigas	Japanese oyster	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
			Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Belgian coast	Offshore buoy	Kerckhof et al., 2007
Crepidula fornicata	Slipper limpet	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2011
			Belgian coast	Offshore buoy	Kerckhof et al., 2007
Isognomum bicolor	Oyster	Sessile	Arraial do Cabo, Brazil	Oil platform	Ferreira et al., 2006
Patella vulgata	Common European limpet	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Perna perna	Brown mussel	Sessile	Gulf of Mexico, Texas, USA	Oil platform	Sheehy and Vik, 2010
			New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010
Porifera					
Monanchora clathrata		Sessile	New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010
Mycale toxifera		Sessile	New Zealand	Semi-submersible oil rig	Hopkins and Forrest, 2010

**Macleod (2013) used off-shore navigation buoys as a proxy for investigating the presence of non-indigenous/invasive/exotic species, which are likely to inhabit off-shore renewable energy structures in that geographic area.   Source: Adapted from Mineur et al., 2012.*

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Appendix 1. Websites and databases

AquaNIS – Information system on aquatic non-indigenous and cryptogenic species
http://www.corpi.ku.lt/databases/index.php/aquanis

Baltic Marine Environment Protection Commission
https://helcom.fi

Ecospeed – Hull Coating
https://subind.net/coatings/ecospeed

European Alien Species Information Network (EASIN)
https://easin.jrc.ec.europa.eu/easin

European Wave and Tidal Energy Conference Series (EWTEC) https://ewtec.org/

GloFouling Partnerships project
https://www.glofouling.imo.org/knowledge

International Maritime Organization
https://www.imo.org/en/About/Conventions/Pages/International-Convention-on-the-Control-of-Harmful-Anti-fouling-Systems-on-Ships-(AFS).aspx

International Seabed Authority
https://www.isa.org.jm/about-isa/

National Estuarine and Marine Exotic Species Information System (NEMESIS)
https://invasions.si.edu/nemesis/

OCEANIC
http://oceanic-project.eu/biofouling-database/

Offshore Solar Power
https://www.rwe.com/en/research-and-development/solar-energy-projects/offshore-solar/

OpenHydro
https://www.emec.org.uk/about-us/our-tidal-clients/open-hydro/

Oslo and Paris Commission (OSPAR)
https://www.ospar.org

PELAMIS wave energy converter
https://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/

PRIMRE
https://openei.org/wiki/PRIMRE/Search?q=biofouling

Submarine Cable Map
https://www.submarinecablemap.com/

Support Vessels
https://www.dco.uscg.mil/OCSNCOE/Renewable-Energy/Support-Vessels/

Tethys
https://tethys.pnnl.gov/summaries/short-science-summary-offshore-wind-farms-stepping-stones-non-indigenous-species

World Register of Introduced Marine Species (WRiMS)
https://www.marinespecies.org/introduced/

Appendix 2. Species identified on offshore renewable energy sites

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Algae					
Acrosiphonia arcta	Arctic sea moss	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Aglaothamnion sp.	Red algae	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Alaria esculenta	Dabberlocks, badderlocks, or winged kelp (brown algae)	Sessile	Orkney, UK	Wave buoy	Want et al., 2017, 2018
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Apoglossum ruscifolium	Veined tongue weed	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Audouinella sp.	Red algae	Sessile	Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Bangia fuscopurpurea	Red algae	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
Blidingia minima	Filamentous green algae	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
			North Sea	Offshore wind farm	Leonhard et al., 2006
Brongniartella byssoides	Brongniart's thread weed	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Bryopsis sp.	Green algae	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Callithamnion corymbosum	red algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Ceramium sp.	Red algae	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Chaetomorpha linum	Green algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Chorda filum	Dead man's rope or sea lace	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Cladophora sp.	Green algae	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
			North Sea	Offshore wind farm	Leonhard et al., 2006
Coccotylus truncatus	Red algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Corallina officinalis	Red algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Cryptopleura ramosa	Fine-veined crinkle whelk	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Cystoseria sp.	Brown algae	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Dasysiphonia (Heterosiphonia) sp.	Red algae	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Dasysiphonia (Heterosiphonia) japonica	Red algae	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Delesseria sanguinea	Sea beech	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Desmarestia aculeata	Desmarests's flattened weed or sea sorrel	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Desmarestia viridis	Brown algae	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Dictyota dichotoma	Forked ribbons	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Ectocarpus siliculosus	Filamentous brown algae	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Ectocarpus sp.	Filamentous brown algae	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
			North Sea	Offshore wind farm	Leonhard et al., 2006
Enteromorpha sp.	Green algae	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Giffordia sp.	Brown algae	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Hildenbrandia rubra	Encrusting red alga	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Hincksia mitchellae	Brown algae	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Laminaria sp.	Brown algae	Sessile	Brittany, France	Submarine power cable	Taormina, 2019
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Lomentaria clavellosa	Club bead-weed or feathery tube weed	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Petalonia fascia	Brown algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Petalonia zosterifolia	Brown algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Phycodrys rubens	Sea oak	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Phyllophora pseudoceranoides	Stalked leaf bearer	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Pilayella littoralis	Brown algae	Sessile	Baltic Sea, Strait of Kalmar, Southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
			North Sea	Offshore wind farm	Leonhard e al., 2006
Plocamium cartilagineum	Cartilaginous cock's comb	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Polysiphonia fucoides	Red algae	Sessile	Baltic Sea, Strait of Kalmar, Southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
Polysiphonia fibrillosa	Red algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Polysiphonia sp.	Red algae	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999; 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Porphyra umbilicalis	Red algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Pterosiphonia sp.	Red algae	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Ralfsia verrucosa	Crustose brown algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Ralfsia sp.	Crustose brown algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Rhodomela confervoides	Straggly bush weed	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Saccorhiza polyschides	Furbellow	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Ultothrix sp.	Green algae	Sessile	Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Ulva (*Enteromorpha*) *clathrata*	Sea lettuce (green algae)	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Ulva (*Enteromorpha*) *linza*	Sea lettuce (green algae)	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Ulva (*Enteromorpha*) *prolifera*	Sea lettuce (green algae)	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
		Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Ulva compressa	Green algae	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
Ulva lactuca	Sea lettuce	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Ulva intestinalis	Sea lettuce (green algae)	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
			North Sea	Offshore wind farm	Leonhard et al., 2006
Ulva spp./*Enteromorpha* spp.	Green algae	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
Ulva sp.	Green algae	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			North Sea	Offshore wind farm	Leonhard et al., 2006
Urospora pencilliformis	Green algae	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Annelida					
Aonides paucibranchiata	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Aphrodita sp.	Polychaete worm	Mobile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Arenicola marina	Lugworm or sandworm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Chaetopterus variopedatus	Parchment worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Chrysopetalum sp.	Polychaete worm	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Cirratulidae	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Dorvilleidae sp.	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Eteone foliosa	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Eulalia viridis	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010, 2011
			North Sea	Offshore wind farm	Leonhard et al., 2006
Eulalia sp.	Polychaete worm	Mobile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Eunereis longissima	Polychaete worm	Mobile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Euzonus flabelligerus	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Gattyana cirrhosa	Scale worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Glycera alba	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Goniadella bobretzkii	Polychaete worm	Mobile	North Sea	Offshore wind farm	DONG Energy, 2006; Leonhard et al., 2006
Harmothoe extenuata	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Harmothoe pachenstegeri	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Harmothoe sp.		Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Heteromastus filiformis	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Hydroides dirampha	Tube-dwelling worm	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Hydroides elegans	Tube-dwelling worm	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Hydroides ezoensis	Tube-dwelling worm	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Hydroides sp.	Worm	Sessile	Northeast coast, Redcar England	Offshore wind farm	Canning, 2020

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Lanice conchilega	Sand mason worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			North Sea	Offshore wind farm	Leonhard et al., 2006
Lepidonotus clava	Scale worm	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Lepidonotus squamatus	Scale worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Magelona mirabilis	Shovelhead worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Marphysa depressa	Polychaete worm	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Myrianida sp.	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010
Nectoneanthes multignatha	Polychaete worm	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Nephtys caeca	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Nephtys hombergii	Cat worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Nephtys longosetosa	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Nereis diversicolor	Polychaete worm	Mobile	Baltic Sea, Strait of Kalmar, Southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
Nereis (*Eunereis*) *longissima*	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Nereis multignatha	Polychaete worm	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Nereis pelagica	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Nereis spp.	Polychaete worm	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Nonparahalosydna pleiolepis	Polychaete worm	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Notomastus latericeus	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Oerstedia dorsalis	Ribbon worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Ophelia borealis	Bristle worm	Mobile	North Sea	Offshore wind farm	DONG Energy, 2006; Leonhard et al., 2006
Orbinia sertulata	Polychaete worm	Mobile	North Sea	Offshore wind farm	DONG Energy, 2006; Leonhard et al., 2006
Pectinaria (Lagis) koreni	Trumpet worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Pholoe synophthalmica	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Pholoe sp.	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Phyllodoce longipes	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Phyllodoce mucosa	Polychaete worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010, 2019
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Pisione remota	Polychaete worm	Mobile	North Sea	Offshore wind farm	DONG Energy, 2006; Leonhard et al., 2006
Polygordius appendiculatus	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Polynoidea spp.	Scale worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
Pomatoceros triqueter	Tube-dwelling annelid worm	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010
Pomatoceros sp.		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Protodorvillea kefersteini	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Rullierinereis sp.	Polychaete worm	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Sabella pavonina	Peacock worm		Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Sabellaria spinulosa	Ross worm	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Scoloplos armiger	Armoured bristleworm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Scolelepsis bonnieri	Polychaete worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Spio filicornis	Bristleworm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Spionidae		Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Spirobranchus tricornis	Encrusting polychaete	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Spirobranchus triqueter	Encrusting polychaete	Sessile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			South North Sea	Offshore wind farm	Kerckhof et al., 2019
			Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2019, 2021
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Syllis gracilis	Worm	Mobile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Travisia forbessi	Bristle worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Ascidiacea					
Ascidiella aspera	European sea squirt	Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2019, 2021
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Ascidiella sp.	Sea squirt	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Botrylloides leachii		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Botryllus schlosseri	Star tunicate	Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2021
			Orkney, UK	Wave buoy	Want et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Ciona intestinalis	Vase tunicate	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Corella eumyota	Orange-tipped sea squirt	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Corella parallelogramma	Gas-mantle ascidian	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Diplosoma listerianum		Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Diplosoma spongiforme		Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2021
Lissoclinum peforatum		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Polyclinum aurantium		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Styela clava	Stalked sea squirt, clubbed tunicate, Asian tunicate, leathery sea squirt, or rough sea squirt	Sessile	Brittany, France	Submarine power cable	Taormina, 2019
Bryozoa					
Aetea anguina		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Aetea sp.		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Alcyonidium sp.		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Bicellariella ciliata		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Bugulina (*Bugula*) *fulva*		Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Callopora dumerilii		Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Callopora sp.		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Cauloramphus sp.		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Celleporella hyalina		Sessile	Orkney, UK	Settlement panels at a Wave/Tidal Energy Site	Want et al., 2019, 2021
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Celleporina hassalli		Sessile	Orkney, UK	Settlement panels at a Wave/Tidal Energy Site	Want et al., 2021
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Conopeum reticulum	Sea mat	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Northern Beibu Gulf, China	Settlement panels at offshore site	Yan et al., 2006
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Crisidia cornuta		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Cryptosula pallasiana	Orange encrusting bryozoan	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Electra bengaliensis		Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Electra pilosa		Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010, 2019
			Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2019, 2021
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
			North Sea	Offshore wind farm	Leonhard et al., 2006
Electra tenella		Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Membranipora grandicella		Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Membranipora limosa		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Membranipora membranacea		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Membranipora savartii		Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Nellia oculata		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Oshurkovia littoralis		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Scruparia ambigua		Sessile	west/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Scrupocellaria diadema		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Scrupocellaria scruposa		Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Savigniella lafontii		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Tubulipora sp.		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Unidentified bryozoan (branched)		Sessile	Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
Cnidaria					
Abietinaria sp.	Hydroid	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Actinia equina	Red beadlet anemone	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
Actiniaria	Anemone	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
			Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			North Sea	Offshore wind farm	Leonhard et al., 2006
Amphisbetia operculata	Hydroid	Sessile	Bay of Sandoyne, UK	Wave buoy	Want et al., 2017, 2018
Campanularia retteri	Hydroid	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Campanulariidae	Hydroid	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Clytia hemisphaerica	Hydroid	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
			Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Clytia sp.	Hydroid	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Diadumene cincta	Orange anemone	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Diaphasia sp.	Hydroid	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Ectopleura larynx	Ringed tubularia	Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2019, 2021
			Orkney, UK	Wave buoy	Want et al., 2017, 2018
Eudendrium sp.	Hydroid	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Filella serratum	Hydroid	Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Halecium sp.	Hydroid	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Halocordyle disticha	Hydroid	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Hebella corrugate	Hydroid	Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Hebella sp.	Hydroid	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Hydractinia echinata	Hydroid	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
			North Sea	Offshore wind farm	Leonhard et al., 2006
Kirchenpaueria pinnata	Fine feather sea fir	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Lytocarpus philippinus	Hydroid	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Metridium dianthus	Plumose anemone	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Metridium senile	Frilled anemone	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2010, 2019
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Obelia bidentata	Hydroid	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Obelia dichotoma	Hydroid	Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2019
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Obelia geniculata	Hydroid	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Obelia spp.	Hydroid	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2010
			Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Opercularella sp.	Hydroid	Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Orthopyxis sp.	Hydroid	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Plumaria setacea	Plumed hydroid or little sea bristle	Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2019, 2021
Pseudogorgia godeffroyi	Organ pipe coral	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Sagartia troglodytes	Cave-dwelling anemone	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010
Sargatia spp.	Elegant anemone	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Sertularia argentea	Sea fir or Neptune plant	Sessile	Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
Tubularia indivisa	Oaten pipes hydroid	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2010, 2019
			Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
			North Sea	Offshore wind farm	Leonhard et al., 2006
Tubularia larynx	Hydroid	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2010
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Tubularia parasitica	Hydroid	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Tubularia sp.	Hydroid	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Urticina felina	Dahlia anemone	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Urticina spp.	Dahlia anemone	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Unidentified hydrozoan (turf)		Sessile	Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Crustacea (barnacles)					
Alepas pacifica	Goose barnacle	Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Balanus amphitrite amphitriate	Acorn barnacle		Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Balanus balanus	Acorn barnacle	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Balanus crenatus	Crenate barnacle	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2010, 2011
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Balanus improvisus		Sessile	Baltic Sea, Strait of Kalmar, Southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
			South North Sea	Offshore wind farm	Kerckhof et al., 2011
Balanus perforatus		Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Balanus poecilotheca		Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
Balanus (Amphibalanus) reticulatus	Reticulated barnacle	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Balanus trigonus	Triangle barnacle	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Balanus zhujiangensis		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Balanus sp.		Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Chirona amaryllis	Acorn barnacle	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Chirona hameri	Acorn barnacle	Sessile	Orkney, UK	Wave buoy	Want et al., 2017, 2018
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Chirona tenuis	Acorn barnacle	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
Conchoderma auritum	Rabbit-ear barnacle	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Conchoderma hunteri		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Conchoderma virgata	Goose barnacle	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Heteralepas japonica	Goose barnacle	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Lepadomorpha sp.		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Lepas anatifera	Gooseneck barnacle	Sessile	North Pacific Ocean	Wave rider buoy	Thomson et al., 2015
			Orkney, UK	Wave buoy	Want et al., 2017
			Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Lepas anserifera	Gooseneck barnacle	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Lepas indica		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Megabalanus coccopoma	Titan acorn barnacle	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Megabalanus tintinnabulum	Acorn barnacle	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
Megabalanus rosa	Acorn barnacle	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Megabalanus volcano	Acorn barnacle	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Megabalanus zebra	Acorn barnacle	Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Semibalanus balanoides	Rock barnacle	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2010, 2011
			Bay of Sandoyne, UK	Wave buoy	Want et al., 2017, 2018
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Solidobalanus ciliatus		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Solidobalanus socialis		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Tetraclita coerulescens		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Tetraclita squamosa squamosa		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Verruca stroemia	Wart barnacle	Sessile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Crustacea					
Atelecyclus sp.	Crab	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Atylus swammerdami	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Bathyporeia guilliamsoniana	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Calanus sp.	Copepod	Mobile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Cancer pagurus	North Sea crab	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Caprella linearis	Skeleton shrimp	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			West/north coasts of Scotland	Navigational buoy	Macleod, 2013*
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
			North Sea	Offshore wind farm	Leonhard et al., 2006
Caprella penantis	Skeleton shrimp	Mobile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Caprella sp.	Skeleton shrimp	Mobile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
			North Sea	Offshore wind farm	Leonhard et al., 2006
Carcinus maenas	European green crab	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Copepoda		Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Corophium (*Monocorophium*) *acherusicum*	Tube-dwelling amphipod	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2010; 2019
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Corophium (*Monocorophium*) *sextonae*	Mud shrimp	Mobile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Corophium volutator	Mud shrimp	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Crangon crangon	Brown shrimp	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Cyclopoida sp.	Copepod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Diastylis sp.	Cumacean		North Sea	Offshore wind farm	Leonhard et al., 2006
Eurysteus nitida [sic]	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Gamarellus angulosus	Amphipod	Mobile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Gammarus locusta	Amphipod	Mobile	Baltic Sea, Strait of Kalmar, southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Gammarus oceanicus	Amphipod	Mobile	Baltic Sea, Strait of Kalmar, southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
Gammarus zaddachi	Amphipod	Mobile	Baltic Sea, Strait of Kalmar, southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
Gitana sarsi	Amphipod	Mobile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Harpacticoida sp.	Copepod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Harpacticus sp.	Copepod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Haustorius arenarius	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Hippolyte varians	Shrimp	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
Homarus gammarus	Lobster	Mobile	Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Idotea balthica	Aquatic sowbug	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Baltic Sea, Strait of Kalmar, southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Idotea pelagica	Aquatic sowbug	Mobile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Idotea sp.	Aquatic sowbug	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Jassa falcata	Tube-dwelling amphipod	Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2021
Jassa herdmani	Tube-dwelling amphipod	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010, 2019
		Sessile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			west/north coasts of Scotland	Navigational buoy	Macleod, 2013; Macleod et al., 2016*
Jassa mamorata	Tube-dwelling amphipod	Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2019
			North Sea	Offshore wind farm	Leonhard et al., 2006

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Jassa spp.	Tube-dwelling amphipod	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Northern Beibu Gulf, China	Settlement panels at offshore site	Yan et al., 2006
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Janiridae	Isopod	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Liocarcinus holsatus	Flying crab	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
Liocarcinus pusillus	Dwarf swimming crab	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Macropodia linaresi	Spider crab	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010
Megaleuropus agilis	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Melita sp.	Amphipod	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Metopa sp.	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Munna sp.	Isopod	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Nanosesarma minutum	Crab	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Necora puber	Velvet swimming crab	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2009
			Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Nototropis swammerdamei	Amphipod	Mobile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Pagurus bernhardus	Common marine hermit crab	Mobile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			South North Sea	Offshore wind farm	Kerckhof et al., 2009
			North Sea	Offshore wind farm	Leonhard et al., 2006

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Parajassa pelagica			West/north coasts of Scotland	Navigational buoy	Macleod, 2013; Macleod et al., 2016*
Perioculodes longimanus	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Phtisica marina	Least skeleton shrimp	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010
Pilumnus hirtellus	Hairy crab	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2009
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Pisidia longicornis	Porcelain crab	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Pisidia sp.	Crab	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Plagusia tuberculata	Crab	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Podocerus sp.	Amphipod	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Pontocratus altamarinus	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Pontocrates arenarius	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Pontocrates sp.	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Pseudocuma longicornis	Cumacean		North Sea	Offshore wind farm	Leonhard et al., 2006

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Stenothoe sp.	Amphipod	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2019
			Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			North Sea	Offshore wind farm	Leonhard et al., 2006
Tanaidacea			North Sea	Offshore wind farm	Leonhard et al., 2006
Thoralus cranchii	Shrimp	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
Westwoodilla caecula	Amphipod	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Echinodermata					
Amphipholis squamata	Brooding snake star or dwarf brittle star	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2019
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Antedon bifida	Rosy feather star	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Asterias rubens	Common sea star	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2010; 2019
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			North Sea	Offshore wind farm	Leonhard et al., 2006
			Northeast coast, Redcar, England	Offshore wind farm	Canning, 2020
Echinocyamus cordatum	Common heart urchin	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Echinocyamus pusillus	Pea urchin	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Echinus sp.	Urchin	Mobile	Northeast coast, Redcar, England	Offshore wind farm	Canning, 2020
Ophiactis maculata	Brittle star	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Ophionereis dubia	Brittle star	Mobile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Ophiotrix fragilis	Common brittlestar	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			Orkney, UK	Wave buoy	Want et al., 2017
			Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Ophiura albida	Brittle star	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Ophiura ophiura	Serpent star	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Ophiura sp.	Brittle star	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Psammechinus miliaris	Green sea urchin	Mobile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2010, 2019
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Mollusca					
Acanthochitona crinita	Chiton	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Aequipecten opercularis (juvenile)	Queen scallop	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Alectryonella haliotidaea		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Alectryonella plicatula		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Angulus tenuis	Thin tellin	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Anomia ephippium	Saddle oyster	Sessile	Orkney, UK	Settlement panels at a Wave/ Tidal Energy Site	Want et al., 2019, 2021
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Arca sp.	Ark clam	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Arctica islandica	Ocean quahog	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Atrina vexillum	Pen shell	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Barbatia uwaensis	Bearded ark clam	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Chamelea gallina	Striped venus clam	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Chlamys pica		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Chlamys radula		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Chlamys sp.		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Crassostrea gigas	Japanese oyster	Sessile	Dutch North Sea coast	Offshore wind farm	KEMA, 2010
Crepidula fornicata	Slipper limpet	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010, 2011
Dendrostrea crenulifera		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Dendostrea folium	Leaf oyster	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Enis americanus	American razor shell	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Fabulina fabula	Bean-like tellin	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Goodallia triangularis		Sessile	North Sea	Offshore wind farm	DONG Energy, 2006; Leonhard et al., 2006
Heteranomia squamula	Saddle oyster	Sessile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			south North Sea	Offshore wind farm	Kerckhof et al., 2010
Hiatella arctica	Wrinkled rock-borer or the arctic saxicave	Sessile	Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
			West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Hiatella orientalis	Clam	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Hyotissa hyotis	Honeycomb oyster	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Isognomon isognomon		Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Isognomon legumen		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999, 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Isognomon nucleus		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Modiolus comptus	Horse mussel	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Modiolus metcalfei	Horse mussel	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Modiolus phaseolina	Horse mussel	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Modiolus philippinarum	Horse mussel	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Modiolus sp.	Horse mussel	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Musculus discors	Discord mussel	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Musculus laevigatus		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Musculus senhousei	Asian date mussel	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Mytilus edulis	Blue mussel	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			South North Sea	Offshore wind farm	Kerckhof et al., 2009, 2010, 2011, 2019
			Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			Bay of Sandoyne, UK	Wave buoy	Want et al., 2017, 2018
			Swedish west coast	Exploratory buoy at offshore wave site	Langhamer, 2010
			Dutch North Sea coast	Offshore wind farm	KEMA, 2010
			Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
			Billia Croo Orkney, Scotland	Wave energy converter	Nall et al., 2017
			North Sea	Offshore wind farm	Leonhard et al., 2006
			Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Mytilus trossulus	Bay mussel or foolish mussel	Sessile	Baltic Sea, Strait of Kalmar, southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
Mytilus sp.		Sessile	west/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Neopycnodonte cocnlear		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Ostrea denselamellosa	Oyster	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Parahyotissa imbricata		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Parahyotissa sinensis		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Parvicardium sp.	Cockle	Sessile	south North Sea	Offshore wind farm	Kerckhof et al., 2009
Perna viridis	Asian green mussel	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Pinctada chemnitzi	Pearl oyster	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Pinctada martensi	Pearl oyster	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Pinctada margartifera	Pearl oyster	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Pinctada nigra	Pearl oyster	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Pinna atropurpurea	Pen shell	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Pinna muricata	Pen shell	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Planostrea pestigris	Flat oyster	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Pteria brevialata		Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Pteria coturnix		Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Pteria dendronephthya		Sessile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Pteria loveni		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Pteria penguin	Penguin's wing oyster	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Saccostrea cucullata	Hooded oyster or Natal rock oyster	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Saccostrea mordax		Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Septifer virgatus	Clam	Sessile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
			Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Spisula elliptica	Elliptical surfclam	Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Spisula solida (juvenile)	Surfclam	Sessile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
			North Sea	Offshore wind farm	DONG Energy, 2006; Leonhard et al., 2006
Talonostrea talonata	Cat's paw oyster	Sessile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Thracia phaseolina		Sessile	North Sea	Offshore wind farm	Leonhard et al., 2006
Venerupis senegalensis	Pullet carpet shell	Sessile	Denmark/North Sea	Offshore wind farm	Bouma and Lengkeek, 2009
			south North Sea	Offshore wind farm	Kerckhof et al., 2010
Mollusca (gastropods)					
Aeolidiella glauca	Sea slug	Mobile	Dutch North Sea coast	Offshore wind farm	KEMA, 2010

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Coryphella sp.	Sea slug	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Cratena sp.	Sea slug	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Crepidula fornicata	Slipper limpet	Mobile	Brittany, France	Submarine power cable	Taormina, 2019
			North Sea	Offshore wind farm	Leonhard et al., 2006
Cycloscla sp.		Mobile	Northern Beibu Gulf, China	Settlement panels at offshore buoy	Yan et al., 2006
Doto sp.	Sea slug	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Epitonium clathratulum		Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2009
Hydrobia ulvae		Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Hydrobia sp.		Mobile	Baltic Sea, Strait of Kalmar, southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
Indomitrella yabei		Mobile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Lacuna sp.	Northern lacuna, wide lacuna, northern chink shell or banded chink shell	Mobile	west/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Littorina littorea	Periwinkle	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
Lymnaea peregra		Mobile	Baltic Sea, Strait of Kalmar, southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
Nudibranchia	Sea slug	Mobile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
Okenia sp.	Sea slug	Mobile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Onchidoris sp.	Sea slug	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Opisthobranchia	Sea slug	Mobile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Patellidae	Limpet	Mobile	Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
Patella pellucidum	Blue-ray limpet	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*

Species	**Common name**	**Mobile or sessile**	**Geographic location**	**Structure type**	**References**
Patella vulgata	Common European limpet	Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Polinices polianus	Moon snail	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Pugilina sp.		Mobile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Rissoa sp.	Minute sea snail	Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Sakuraeolis sp.	Sea slug	Mobile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2000
Serpulorbis sp.	Worm snails or worm shells	Mobile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Theodoxus fluviatilis		Mobile	Baltic Sea, Strait of Kalmar, southeastern Sweden	Offshore wind farm	Wilhelmsson and Malm, 2008
Trivia monacha	European cowrie or spotted cowrie	Mobile	west/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Vermetus renisectus	Worm snails or worm shells	Mobile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Vermetus sp.	Worm snails or worm shells	Mobile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Nemertea					
Emplectonema gracile	Green ribbon worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
Emplectonema neesii	Ribbon worm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
Emplectonema sp.	Ribbon worm	Mobile	Northeast coast, Redcar England	Offshore wind farm	Canning, 2020
Nematoda		Mobile	Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
			North Sea	Offshore wind farm	Leonhard et al., 2006
Nermertini	Ribbon worm	Mobile	North Sea	Offshore wind farm	Leonhard et al., 2006
Platyhelminthes					
Leptoplana tremellaris	Flatworm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2010
Pleioplana atomata	Flatworm	Mobile	South North Sea	Offshore wind farm	Kerckhof et al., 2011
Ramphogordius sanguineus		Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Stylochoplana sp.		Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*

Species	Common name	Mobile or sessile	Geographic location	Structure type	References
Turbellaria	Flatworm	Mobile	Zhujiang River Delta, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 2003
Porifera					
Alcyonium digitatum	Dead man's fingers (soft coral)	Sessile	Southern Bight of the North Sea	Offshore wind farm	Zupan et al., 2023**
			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Esperiopsis fucorum	Shredded carrot sponge	Sessile	Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
Grantia compressa		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Halichondria sp.		Sessile	Narrows of Strangford Lough, Northern Ireland	Marine current turbines	Royal Haskoning, 2011
Leucosolenia sp.		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Sycon cilatum		Sessile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Pycnogonida	Sea spider	Mobile	Northern Beibu Gulf, China	Settlement panels at offshore site	Yan et al., 2006
			Hainan Island, northern South China Sea	Settlement panels at offshore buoy	Yan et al., 1999
Endeis sp.		Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Nymphon brevirostre		Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*
Phoxichilidium femoratum			Billia Croo, Orkney, Scotland	Wave energy converter	Nall et al., 2017
Pycnogonum sp.		Mobile	West/north coasts of Scotland	Navigational buoy	Macleod et al., 2016*

*****Hydrozoa, Bryozoa, Porifera and Ascidiacea were present but not included in the analysis because specimens were damaged during the sampling process.***

**Macleod (2013) and Macleod et al. (2016) used off-shore navigation buoys as a proxy for investigating the presence of non-indigenous/invasive species, which are likely to inhabit off-shore renewable energy structures in that geographic area.*

Notes: While the presences of one or few individuals does not guarantee a resulting introduction, it is important to be aware of the presence of potential IAS species and to document their appearances to guide future mitigation and control measures (see also Rocha et al., 2013). See Table 3 for species specifically noted as non-indigenous/invasive.

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Acronyms

AFS	Anti-fouling system
ALARP	As low as reasonably practicable
BFMP	Biofouling management plan
BFRB	Biofouling record book
CCTV	Closed-circuit television
CPFs	Central processing facilities
CRMS	New Zealand Craft Risk Management Standard (CRMS)
FLNG	Floating liquified natural gas (FLNG) Facilities
FPSO	Fuel production, storage and offtake facilities
IAS	Invasive aquatic species
IMO	International Maritime Organization
MGPS	Marine growth prevention system
MODU	Mobile offshore drilling unit
ROV	Remote operated vehicle
RSS	Riser support structure
U-WILD	In lieu of dry-dock (U-WILD)
VRASS	Vessel risk assessment score sheets

Definitions

(from the 2011 *IMO Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species*)

Biofouling: The accumulation of aquatic organisms such as micro-organisms, plants, and animals on surfaces and structures immersed in or exposed to the aquatic environment. Biofouling can include microfouling and macrofouling.

Macrofouling: Large, distinct multicellular organisms visible to the human eye such as barnacles, tubeworms, or fronds of algae.

Microfouling: Microscopic organisms including bacteria and diatoms and the slimy substances that they produce. Biofouling comprised of only microfouling is commonly referred to as a slime layer.

Niche areas: Areas on a ship that may be more susceptible to biofouling due to different hydrodynamic forces, susceptibility to coating system wear or damage, or being inadequately, or not, painted, e.g.,, sea chests, bow thrusters, propeller shafts, inlet gratings, dry-dock support strips, etc.

Ship: A vessel of any type whatsoever operating in the aquatic environment and includes hydrofoil boats, air-cushion vehicles, submersibles, floating craft, fixed or floating platforms, floating storage units (FSUs) and floating production storage and off-loading units (FPSOs).

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IOC TECHNICAL SERIES Nº 174

Biofouling prevention and management in offshore renewable energy infrastructure and construction

Best Practices in Biofouling Management — Volume 3

This report is one of a series covering best practices for biofouling management and addressing Invasive Aquatic Species (IAS) for non-shipping sectors, as part of the GloFouling Partnerships project being undertaken by the International Maritime Organization (IMO), in collaboration with the Global Environment Facility (GEF) and the United Nations Development Programme (UNDP).

The focus of these reports is biofouling management: information about the general processes of biofouling, the ecological and environmental impacts, economics of management, and the costs estimated to be associated with IAS are beyond the scope of these reports.

This report addresses specifically biofouling management in relation to offshore renewable energy operations, equipment, and infrastructure. It covers renewable energy generators, pipelines, cables, pipes, monitoring stations and buoys, mining, and mobile associated equipment (support vessels, ROV, AUV).

Biofouling on offshore renewable structures and associated equipment represents significant pathways for the introduction of IAS to offshore project areas and adjacent coastal areas. Management of biofouling should be a core environmental obligation for Offshore Renewable Energy (ORE) project operators, especially in cases where biofouling management requirements are not mandated. Maritime industries, including the newly developing ORE efforts, need to become proactive in their approaches to issues concerning biofouling, biodiversity, and protection of environments. This report presents a review of available information and a suite of recommendations for control of biofouling on these structures.

For further information, visit the GloFouling website at
https://www.glofouling.imo.org

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