Programme Area: Nuclear

Project: Natural Hazards Phase 3

Title: Volume 11: Marine Biological Fouling

Abstract:

This technical volume addresses:

- Introduction
- Description of the main phenomena
- Observations, measurement techniques and modelling tools
- Methodologies
- Related phenomena
- Regulation
- Emerging trends

Context:

The Natural Hazards Review project will develop a framework and best practice approach to characterise natural hazards and seek to improve methodologies where current approaches are inefficient. This is to improve energy system infrastructure design and the project is intended to share knowledge of natural hazards across sectors. The project will be completed in three stages. Phase one will focus on a gap analysis. Phase two will look at developing a series of improved methodologies from the gaps identified in phase one, and phase three will demonstrate how to apply these methodologies. Finally, phase 3 will develop a “how to” guide for use by project engineers.

Enabling Resilient UK Energy Infrastructure:
Natural Hazard Characterisation Technical Volumes
and Case Studies

Volume 11:

Marine Biological Fouling

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Legal Statement

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0.1	29/03/18	Submitted for IPR
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This document forms part of the Energy Technologies Institute (ETI) project 'Low Carbon Electricity Generation Technologies: Review of Natural Hazards', funded by the ETI and led in delivery by the EDF Energy R&D UK Centre. The aim of the project has been to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impact that natural hazards may have on new and existing infrastructure. This work is seen as vital given the drive to build new energy infrastructure and extend the life of current assets against the backdrop of increased exposure to a variety of natural hazards and the potential impact that climate change may have on the magnitude and frequency of these hazards.

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the ETI and authored by EDF Energy R&D UK Centre, with the Met Office and Mott MacDonald Limited. The ETI was active from 2007 to 2019, but to make the project outputs available to industry, organisations and individuals, the ETI has provided a licence to the Institution of Mechanical Engineers and Institution of Chemical Engineers to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The technical volumes outline the latest science in the field of natural hazard characterisation and are supported by case studies that illustrate how these approaches can be used to better understand the risks posed to UK infrastructure projects. The documents presented are split into a set of eleven technical volumes and five case studies.

Each technical volume aims to provide an overview of the latest science available to characterise the natural hazard under consideration within the specific volume. This includes a description of the phenomena related to a natural hazard, the data and methodologies that can be used to characterise the hazard, the regulatory context and emerging trends. These documents are aimed at the technical end-user with some prior knowledge of natural hazards and their potential impacts on infrastructure, who wishes to know more about the natural hazards and the methods that lie behind the values that are often quoted in guideline and standards documents. The volumes are not intended to be exhaustive and it is acknowledged that other approaches may be available to characterise a hazard. It has also not been the intention of the project to produce a set of standard engineering 'guidelines' (i.e. a step-by-step 'how to' guide for each hazard) since the specific hazards and levels of interest will vary widely depending on the infrastructure being built and where it is being built. For any energy-related projects affected by natural hazards, it is recommended that additional site- and infrastructure-specific analyses be undertaken by professionals. However, the approaches outlined aim to provide a summary of methods available for each hazard across the energy industry. General advice on regulation and emerging trends are provided for each hazard as context, but again it is advised that end-users investigate in further detail for the latest developments relating to the hazard, technology, project and site of interest.

The case studies aim to illustrate how the approaches outlined in the technical volumes could be applied at a site to characterise a specific set of natural hazards. These documents are aimed at the less technical end-user who wants an illustration of the factors that need to be accounted for when characterising natural hazards at a site where there is new or existing infrastructure. The case studies have been chosen to illustrate several different locations around the UK with different types of site (e.g. offshore, onshore coastal site, onshore river site, etc.). Each of the natural hazards developed in the volumes has been illustrated for at least one of the case study locations. For the sake of expediency, only a small subset of all hazards has been illustrated at each site. However, it is noted that each case study site would require additional analysis for other natural hazards. Each case study should be seen as illustrative of the methods outlined in the technical volumes and the values derived at any site should not be directly used to provide site-specific values for any type of safety analysis. It is a project recommendation that detailed site-specific analysis should be undertaken by professionals when analysing the safety and operational performance of new or existing infrastructure. The case studies seek only to provide engineers and end-users with a better understanding of this type of analysis.

Whilst the requirements of specific legislation for a sub-sector of energy industry (e.g. nuclear, offshore) will take precedence, as outlined above, a more rounded understanding of hazard characterisation can be achieved by looking at the information provided in the technical volumes and case studies together. For the less technical end-user this may involve starting with a case study and then moving to the technical volume for additional detail, whereas the more technical end-user may jump straight to the volume and then cross-reference with the case study for an illustration of how to apply these methodologies at a specific site. The documents have been designed to fit together in either way and the choice is up to the end-user.

The documents should be referenced in the following way (examples given for a technical volume and case study):

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Volume 1 — Introduction to the Technical Volumes and Case Studies. IMechE, IChemE.

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Case Study 1 — Trawsfynydd. IMechE, IChemE.

Contents

Marine biofouling, or biological fouling, is the undesirable growth of marine organisms (both plants and animals) on man-made structures that are submerged for a sustained period; e.g. boats, buoys, jetties and piers, and the bases of offshore installations such as oil rigs and wind turbine foundations. The species which cause biofouling are perfectly adapted to colonising naturally-occurring hard ***substrates****, such as rocky seashores; so the accumulation of marine growth on man-made structures is to some extent inevitable, despite ongoing advances in anti-fouling paints and coatings.

The life histories of biofouling species are characterised by a free-swimming or planktonic juvenile phase, which drifts on the ocean currents until it comes into contact with a suitable hard surface to colonise. The subsequent adult form attaches firmly to this surface and extracts nutrients from the water column. Common biofouling colonisers include barnacles, mussels, tubeworms, anemones and seaweed. The colonisation of ***sessile*** (fixed/immobile) biofouling species then attracts mobile species such as fish and crustaceans.

Biofouling causes problems by increasing surface complexity, load and hydrodynamic drag on a structure. It can accelerate corrosion, compromise mechanical integrity and ultimately cause system failure. More than 4000 biofouling species have been reported globally (*Cao et al., 2011*). During the recent decommissioning of piled wind turbines, from the Solway Firth (UK), hard fouling of up to 300 millimetres (mm) thickness was observed on the upper 2 to 3 metres (m) of the submerged structure. Around 40 different species of sessile marine growth were recorded on the North Sea oil platform Montrose Alpha, including seaweed and kelp, mussels, *hydroids* and *bryozoans* (*Forteath et al., 1982*).

Whilst biofouling may be a concern for engineers, the creation of artificial reefs can be a positive outcome in terms of habitat creation and biodiversity. Before the onset of industrial fisheries, large areas of the southern North Sea were covered in natural reefs, many of which are now lost (*van der Stap et al., 2016*). In contrast, many thousands of artificial structures are now present in the North Sea in the form of shipwrecks, wind farms and oil and gas platforms; and thousands more will be installed in the near future.

Coastal power stations that utilise seawater in a *once-through cooling water system* can also suffer from biofouling within the system. If untreated, this will impede water flow and drastically

*All technical terms marked in blue can be found in the Glossary section.

reduce the efficiency of heat transfer condensers. However, the semi-enclosed nature of these systems allows the water itself to be dosed with anti-fouling chemicals. This is currently an effective solution which generally keeps the issue within manageable levels. However, future changes in environmental permitting of chemical discharges could make the current solution unavailable. New, alien or invasive biofouling species could be more resistant to even the current treatment. The control of fouling in water intakes, piping systems and desalination plants is estimated to cost over $15 billion per year (*Faimali, 2014*).

Nevertheless, due to the current availability and efficacy of chemical dosing treatments, once-through cooling water systems are currently more vulnerable to clogging by mobile (i.e. non-colonising) marine organisms such as jellyfish, fish and seaweed (that has broken away from the sea floor). This phenomenon may be interchangeably referred to as biofouling, biological clogging or marine ingress. Either way, it is a significant hazard identified by this project for further consideration within this technical volume. In 2011, Torness Nuclear Power Station was shut down for 11 days due to very high volumes of jellyfish being sucked into the cooling water system. This was an exceptional event at Torness, but similar incidents have occurred at power stations and desalination plants around the world. Seaweed ingress causes more frequent, but less severe, generation losses at Torness; whilst Dungeness Power Station has occasionally lost generation due to the sudden ingress of large schools of sprat and herring.

This technical volume is structured as follows: *Section 2* describes the marine biofouling hazard and the processes by which it occurs. *Section 3* provides examples of biofouling from the literature, and introduces a new dataset developed for this volume after previously identifying a significant gap in the evidence base. *Section 4* describes the best current methodologies for characterising the biofouling hazard, based largely on the newly commissioned dataset. *Section 5* notes that no specific minor phenomena associated with marine biological fouling have been identified within the scope of the project. *Section 6* provides an overview of the current engineering standards and guidelines related to marine biofouling, and a brief comment on the absence of directly relevant Regulatory Instruments. *Section 7* discusses how the biofouling hazard is likely to change in the future, due to climate change, invasive alien species and the inherently dynamic nature of the marine environment.

Following the immersion of a new man-made structure, the development of biofouling communities follows a pattern of colonisation and succession as shown in *Figure 1*. The substrate becomes coated with a *biofilm* composed of organic material which then attracts primary and secondary colonisers onto the surface, forming the *microfouling* community. The next stage involves the settlement of larvae and spores of tertiary colonisers such as seaweeds, mussels and barnacles which develop into the *macrofouling* community.

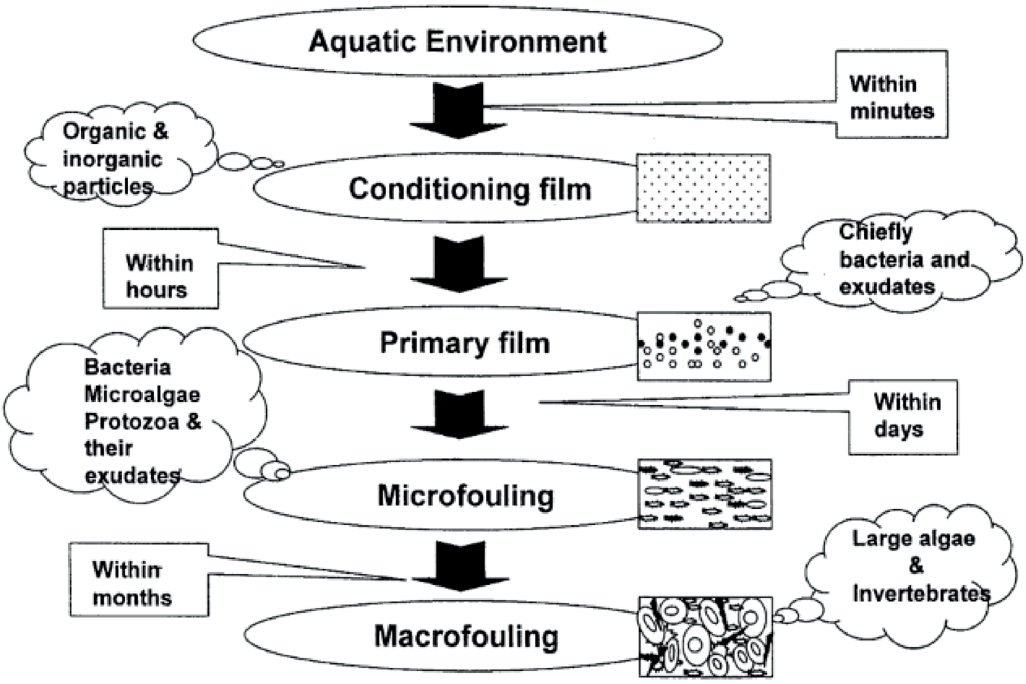

Figure 1. Stages in the development of a stable biofouling community (Nandakumar and Yano, 2003).

The process is remarkably rapid (*Table 1* provides a colonisation timeline). The biofilm formation occurs within the first minutes of biological settlement (*DNV, 2014*). The colonisation of bacteria occurs after approximately 1 to 2 hours. This is followed by spores of *macroalgae* and *diatoms* appearing within the first week, and then the settlement of macrofouling larvae on microbial and algal films (*Abarzua and Jakubowski, 1995*). Biofilm creation alters the physical, chemical and electrical interface between the substrate and the seawater, thus affecting corrosion rates. In turn, corrosion changes the metal surface, which influences biofilm formation (*Dexter, 1993*).

Table 1. Colonisation timeline for microfouling and macrofouling organisms (Tulcidas, 2014).

Timeline	Process
After a few minutes	The physical adhesion of proteins, polysaccharides, glycoproteins and others occurs.
After 24 hours	The reversible absorption of bacteria and unicellular algae occurs. These colonising microorganisms secrete extracellular polymeric substances (EPS) to enclose and hold the substrate, forming a microbial film known as biofilm.
After a few days	The biofilm feeds spores of microalgae. The biofilm generated and the EPS secreted creates a gel matrix providing a high resistance to biocides and protection from predators and environmental variation.
After 2 to 3 weeks	The biofilm can attract more particles and organisms as larvae of marine microorganisms. The roughness of the surface created by the irregular microbial communities will also help the accommodation of the new attracted organisms.

For the purposes of this technical volume, biofouling also includes the clogging of once-through cooling water systems by mobile (i.e. non-colonising) marine organisms such as jellyfish, fish and seaweed that has detached from the sea floor. This is alternatively known as biological clogging or marine ingress.

Coastal power stations (both nuclear and fossil fuel) continuously abstract high volumes of seawater, primarily for efficient operation of their steam turbine generators. Current abstractions are up to a maximum of 50 cubic metres per second but future abstractions, e.g. Hinkley Point C, could be much higher. It is inevitable that such high volumes of seawater will contain marine life, so the cooling water intakes include self-cleaning screening systems, designed to filter out debris and allow an unimpeded flow of cooling water. Most of the time these systems operate very well; however, there are occasions when the systems are overwhelmed by exceptionally high volumes of material due to seasonal periods of high growth and productivity.

The problem material can be divided into three main categories, which occur under different circumstances: jellyfish, seaweed and schooling fish. Jellyfish blooms occur during the summer months, generally under calm conditions. Seaweed ingress occurs during, and immediately after, storm events which produce waves with sufficient energy to tear seaweed from the sea floor. Severe seaweed ingress therefore generally occurs over autumn and winter periods. Severe fish ingress is much more difficult to predict as, unlike seaweed and jellyfish, fish do not simply drift with the prevailing currents.

Biofouling studies are reported in the literature. For example, *Forteath et al. (1982)* assessed marine growth on the North Sea oil platform Montrose Alpha. Marine growth samples were collected at five elevation levels during July and August between the years 1977 and 1980. In all, 45 different species were recorded, of which 40 were sessile forms. The greatest cover was found in the depth range from ***mean low water*** (MLW) to –31 m below MLW, and the least was found between –71 m below MLW and the mud-line (at –91 m below MLW). The species that dominated biofouling at the different depths are shown in *Table 2*.

Table 2. Species dominating biofouling at different depths on the North Sea oil platform Montrose Alpha (Forteath et al., 1982).

Depth	Biofouling species
Sunlit surfaces (MLW to –10 m)	Large amounts of seaweed and kelp. Some plants reached a length of 2.5 m but most were about 1.5 m. The common mussel (*Mytilus edulis*) did not form beds but individuals were scattered amongst the seaweeds, many of them overgrown by ***epiphytes***.
–10 m to –31 m	The seaweeds rapidly gave way to hydroids and bryozoans.
–31 m to –51 m	***Arborescent*** bryozoans were steadily replaced by ***calcareous*** bryozoans.
–51 m to –71 m	The calcareous bryozoans were largely replaced by encrusting bryozoan species. Extensive mats of *Alcyonidium hirsutum* (Fleming) were formed. Small aggregations of tubeworms also became present at the lower depths.
–71 m to mud-line (–91 m)	In general, there was very little biofouling. Discrete masses of tubeworms and deep-water barnacles were present.

van der Stap et al. (2016) assessed the biofouling ***assemblages*** on five gas platforms in the southern North Sea to investigate the effects of depth, and distance offshore. The five platforms were sited on a gradient of increasing distance (from 48 km to 177 km) offshore, and at depths of between 27 m and 43 m (*Figure 2*). In all, 30 different taxa were identified. The three platforms furthest offshore (P3 to P5) became fully covered with marine fouling at all depths, whereas some legs of P1 and P2 were not fully covered, suggesting that biofouling increased with distance from the shore. The abundance of marine fouling was also found to be depth dependent with an initial increase in species richness until 15 to 20 m deep and then a decrease below that.

In the depth range 0 to 20 m, the blue mussel (*Mytilus edulis*) was often present, especially on P1 and P2. It was more abundant on P4 than P3 and P5, suggesting that the blue mussel is an early coloniser of offshore structures (P4 had been installed for three years, compared to seven years for P3 and 13 years for P5). The soft coral (*Alcyonium digitatum*) was only observed on platforms P3 to P5, suggesting that its abundance correlated positively with distance from shore, in line with the pattern found in shipwrecks in the Belgian part of the North Sea (*Zintzen and Massin, 2010*). Trends in other species were also found, but not all variability could be explained by depth or distance from the shore, indicating that other environmental variables play a role, e.g. salinity, water temperature, water currents, food supply, light penetration, silt content and the position on the leg (interior/exterior) in relation to the direction of the current.

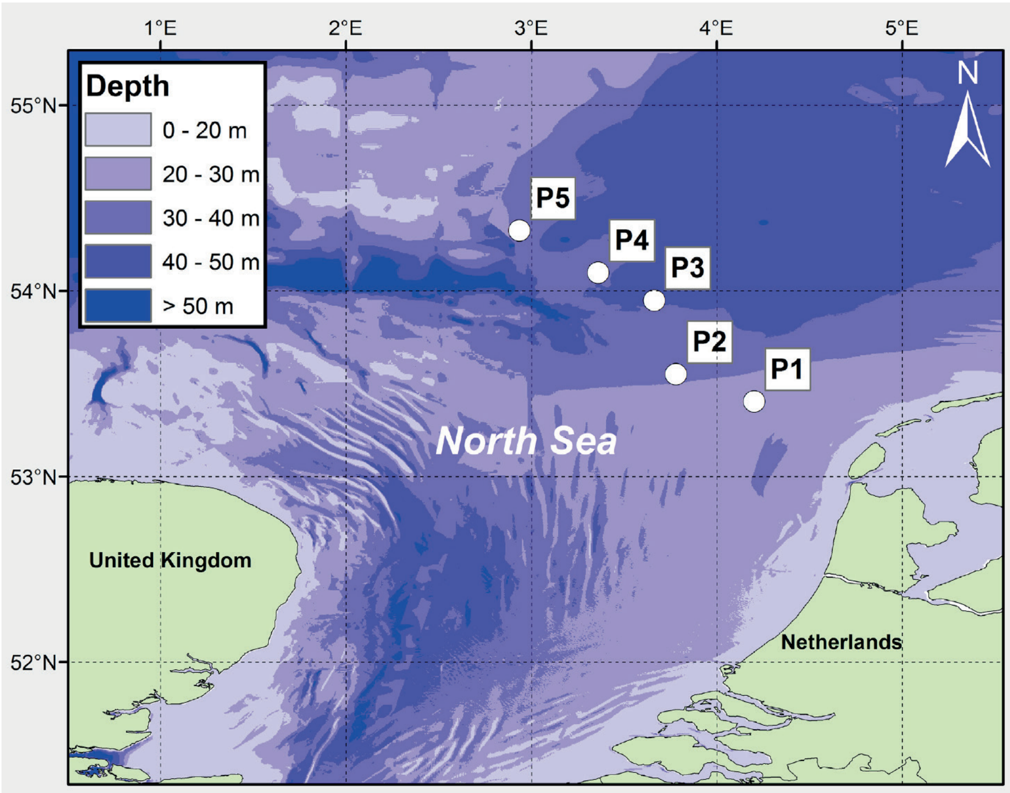

Figure 2. Locations of the platforms P1 to 5 (van der Stap et al., 2016).

One industry knowledge gap that has been identified is the limited understanding of the phenomena relating to the biological fouling of cooling water intakes. It was recognised that the species responsible for this, their biological behaviour, and the mechanisms transporting them in the ocean were not well reported or understood. Consequently, HR Wallingford was commissioned, in 2015, to produce an inventory of the species responsible for biological clogging within the North Sea and European Atlantic coastal waters, and an analysis of the biological traits of these species which lead to biological clogging. The scope of this task was subsequently expanded to include marine species which cause biofouling by colonising marine structures; however, microorganisms were excluded.

A literature search was undertaken to elucidate which species have been previously implicated in fouling events, or may have the potential to cause significant nuisance. Additionally, EDF Energy supplied operational experience data from their coastal power station assets. Two methods of fouling by marine organisms were considered:

- those species which settle on the artificial substrates provided by power assets within or adjacent to the marine environment (such as those in the intertidal or splash zones), termed 'colonisers'; and
- those species which clog screens and/or intake pipelines as a result of being carried by currents, wave or wind action, referred to as 'mobile' (including species with active but insufficient locomotion velocity to escape the water currents generated by the intakes).

It should be noted that some species present a hazard through both methods of fouling. All species identified in the literature search or notified by EDF Energy as either having caused nuisance or considered to carry a significant risk of causing nuisance were noted to provide a species list. The literature was also searched for the functional traits of the species identified, along with larval duration, settling information and any information which might clarify potential proliferation conditions. The included functional traits were:

- growth rate;
- minimum salinity (the minimum salinity tolerated by the species, to understand how far up an estuary it might extend into brackish waters);
- spawning time (the time of year when the organism is actively reproducing);
- life expectancy;
- depth range;
- geographical distribution;
- temperature triggers (temperatures which could encourage the start of a bloom or extensive growth);
- nutritional triggers (food availability which could encourage the start of a bloom or extensive growth);
- preferred substrate;
- larval/*propagule* dispersal potential (how far larvae or propagules can successfully travel away from the parent organism);
- larval vertical mobility (the speed at which larvae can propel themselves up through the water column);
- settling velocity (the speed of current which does not discourage attachment to the substrate);

- larval duration (the period of time for which larvae live prior to metamorphosis);
- larval transportation current (the speed at which larvae disperse);
- vertical mobility (the speed at which adult organisms can propel themselves up through the water column);
- horizontal mobility (the speed at which adult organisms can propel themselves across the water column); and
- any useful supplemental information.

The resulting dataset was organised into a database which consolidates the available scientific information on which species cause biofouling and biological clogging, where they occur, and the life traits that enable them to cause the hazard.

As this is an emerging field, there is a limited understanding of the species responsible for biofouling, their biological behaviour, and the mechanisms transporting them in the ocean. As a result, industry standard hazard characterisation methods do not currently exist.

In addition, given the general lack of data and understanding about the different species, is it not possible to undertake a frequency analysis to assess the severity of an extreme marine biofouling event at a particular site. However, when assessing the risk posed by marine biofouling, the following steps may be followed:

1) identify the nuisance species that may cause a risk at the site of interest;
2) identify the biofouling mechanisms that could impact the type of infrastructure, and narrow down the list of species that need to be considered;
3) take into account the hydrodynamic factors at the site of interest;
4) develop appropriate mitigation strategies.

The rest of this section considers the steps above and provides guidance on how to characterise the hazard. The focus of this technical volume is on the characterisation of the hazard, and more detail is provided on steps 1) to 3) in *Sections 4.1* to *4.3*. Mitigation strategies are briefly mentioned in *Section 4.4*; however, these will vary greatly from site to site, and site-specific examples are provided in Case Study 2 — Dounreay and Case Study 3 — Hunterston.

Throughout this section, the new information provided by the HR Wallingford marine species database is used (introduced in *Section 3*). The new dataset is expected to be the most comprehensive tool for characterising this natural hazard, although it should be recognised that this work was a snapshot of the information available at the time (2016) and, as such, it may already be out of date and should be used with caution.

4.1 Identifying nuisance species

In all, 61 discrete species were identified for the UK, with one indeterminate species being recorded (a record of clogging referred to 'pipefish', of which there are several species within the area under consideration). Some of the species listed have been directly recorded as providing nuisance to existing power assets, with others providing sufficient scope for nuisance to be included. It is possible that more hydroid species than the four identified could cause nuisance, but without current evidence, further hydroid species were excluded.

The spatial distribution of each species was mapped, using International Council for the Exploration of the Sea (ICES) statistical areas (*Figure 3*). These areas were developed to give approximate biogeographical regions of the seas of north-west Europe, for the purpose of managing fisheries, so they correspond well to other ecosystem components and are therefore appropriate for identifying the occurrence of biofouling species. As outlined above, the species occurrence maps do not provide a hazard frequency estimate, but are a first step for better understanding which species could impact upon the site of interest.

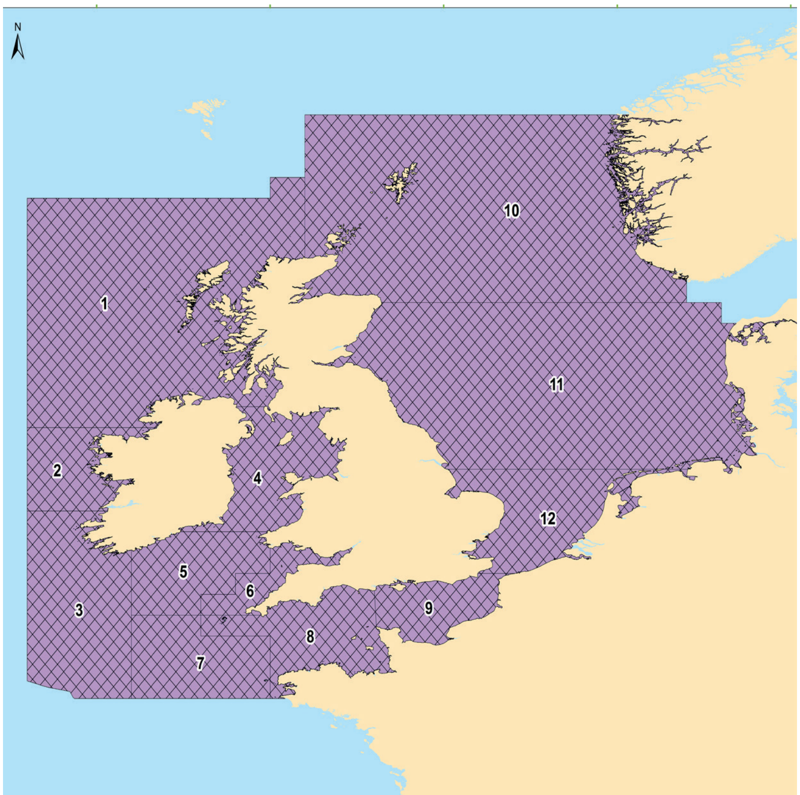

Figure 3. ICES statistical areas (source: ICES website: http://geo.ices.dk/index.php).

There were nine main groups of nuisance species, each of which are considered below:

Seaweeds and kelps

Seaweeds and kelps are shoreline, intertidal and relatively shallow-water species, relying on sunlight to provide their energy requirements (by photosynthesis). In suitable locations, seaweeds can form large and complex areas of dense growth, e.g. 'kelp forests', creating their own ecosystems which provide valuable services such as wave energy absorption, climate change mitigation and optimum habitats for other species, including biofouling species such as hydroids, crustaceans, molluscs, polychaetes and fish. Kelps are some of the fastest growing plant species on Earth and can increase biomass extremely rapidly. They commonly grow in very similar depths (2 to 20 m) to the placement of water intakes. They typically attach to hard substrates, so can directly impede flows or add structural stress. They may also attach at distance from power assets; but their attachment is less tenacious than that of molluscs or sea squirts. During stormy weather with associated high wave action, seaweeds and kelps can break free and become a drifting mass, prone to matting and clogging water intake screens.

Seagrasses

Seagrasses generally colonise sandy areas, growing in dense thickets. They only become a nuisance species when stormy weather breaks their blades, and they become a drifting mass, prone to matting and clogging water intake screens.

Jellyfish and ctenophores

Given suitable conditions, jellyfish and ***ctenophores*** can proliferate heavily during the summer months, creating blooms of many tonnes. They are autonomously ***motile***, but their mobility is generally limited to selecting their vertical position (height) within the water column. As such, jellyfish largely drift with the prevailing hydrodynamic conditions, in the horizontal plane. If the prevailing hydrodynamic conditions drive them towards a cooling water intake, they will be unable to escape, leading to a high clogging hazard to intake screens.

Bivalves and gastropods

Biofouling organisms release their juveniles or gametes into the water column, where they spend a portion of their life cycle as plankton, before settling and colonising a hard substrate. Although zooplankton are generally free-swimming, their microscopic size means that their autonomous motility is limited to finding prey species within the plankton, and following the diurnal vertical migrations of other plankton within the sea surface layers. In this respect, they are similar to jellyfish.

Eventually, these animals settle on hard surfaces and attach tenaciously, in many cases forming large colonies of adult animals, e.g. mussel beds. These can impede flows within pipework or turbines, or add considerable weight or hydrodynamic drag and thus increase structural stress on materials used to construct wind farm turbine foundations or oil rig legs. They have a planktonic larval stage which allows the animals to spread over large areas, drifting considerable distances with the water currents during a period of long larval viability.

Barnacles

Barnacles also settle tenaciously on hard surfaces, and are particularly adept at exploiting any available area, so despite the small size of individuals, they can create significant encrusting in relatively short time periods. Their planktonic larval stage also allows them to disperse and colonise over large distances.

Sea squirts

Sea squirts also settle tenaciously on hard surfaces (*Aldred and Clare, 2014*), acting similarly to the way described for molluscs, but their shorter larval phase means that their potential to move over distances is more restricted.

Hydroids and anemones

Hydroids and anemones also settle on hard surfaces, acting similarly to molluscs and sea squirts. They also have limited larval stages which prevent dispersion over large distances. However, the anemones can be extremely long-lived. Hydroids which have settled on nearby hard surfaces can be broken in stormy weather and become a drifting mass, prone to matting and clogging water intake screens. In autumn, some species preferentially shed 'branches' which become drifting masses.

Tubeworms

The nuisance worms are all tube-building species, which typically attach to hard substrates. Their tubes are calcareous and can in some cases mass together to form large reef-like hard structures, e.g. *Sabellaria* reefs.

Fish

Fish possess considerably more autonomous motility than other biofouling species, but some fish are more mobile than others. *Benthic* species (e.g. flat fish) spend much of the time stationary on the seabed, whilst pelagic (open sea) species (e.g. mackerel, herring, tuna) are highly mobile, and able to cover large distances at high speeds, and against prevailing currents. Generally, fish do not cause frequent marine ingress problems in the UK. They occur steadily in small numbers — usually benthic individuals which stray into the influence of the intake — and the cooling water filtering systems are designed to deal with this. When fish do cause problems, it is due to the sudden ingress of a large school of pelagic fish, most commonly sprat or herring. As previously mentioned, these species are highly mobile, and their location is not directly driven by the hydrodynamic mechanisms discussed below. Rather it is generally driven by large-scale breeding and feeding behaviour. The distribution of prey species will be influenced by the temperatures and currents of different water bodies, so this is indirectly linked with hydrodynamic mechanisms. However, the most likely reason for significant fish ingress events is that a school is driven into the intakes by predators. These are chance events which cannot be easily predicted, and certainly cannot be linked to hydrodynamic mechanisms. It may be possible to identify a degree of risk, associated with the large-scale distribution and abundance of these species, but that is beyond the scope of this report.

4.2 Identifying biofouling mechanisms

Once the species of interest have been identified, it is necessary to better understand the different biofouling mechanisms. Certain species will cause certain types of biofouling; if a piece of infrastructure is not affected by a certain type of biofouling then it may be possible to narrow down the list of species that need to be investigated further. The variety of mechanisms, by which the different groups of organisms can cause nuisance, are summarised in *Table 3*. The terms used are:

- clogging — where organisms impinge on screens or obstruct pipes;
- colonising — where organisms settle on the surfaces of power asset infrastructure;
- structural stress — where organisms that have settled on the surface add either excess weight or hydrodynamic drag which threaten the structural integrity of a power asset;
- calcareous component — where the organism produces strong shells or tubes composed primarily of calcium carbonate, which are highly resistant to removal;
- strong attachment — where the organism cements itself to substrates with a biological 'cement' or 'glue';
- form debris mats — where organisms or parts of organisms aggregate to form mats or clumps of material which can clog intake screens. These are rarely composed of only one species — they often contain various seaweeds and kelps and, depending on the season, possibly seagrasses and hydroids. This mix of species tends to form stronger mats which present more of a hazard than individual species, e.g. most of the hydroid species form smaller colonies than the seaweeds and present less hazard on their own. Material from anthropogenic sources, e.g. plastics, may also be incorporated.

Table 3. Summary of the mechanisms by which each group of organisms cause a biofouling hazard.

Group	Clogging	Colonising	Structural stress	Calcareous component	Strong attachment	Form debris mats
Jellyfish and ctenophores	✓					
Bivalves and gastropods	✓	✓	✓	✓	✓	
Sea squirts		✓			✓	
Seaweeds	✓	✓			✓	✓
Fish	✓					
Hydroids and anemones	✓	✓			✓	✓
Barnacles		✓		✓	✓	
Seagrasses	✓					✓
Tubeworms		✓		✓	✓	

It is worth noting the importance of anthropogenic factors on biofouling. Global shipping and marine debris, such as plastics, are responsible for transporting biofouling species around the world. Man-made structures provide an extensive network of habitats to encourage and extend the distribution of biofouling species. Shellfish farming (aquaculture) can be a source of biofouling larvae.

A more detailed summary of the biofouling mechanisms for different organisms is provided below. *Section 4.2.1* provides more information for species that are either seen as a priority for UK infrastructure or have more available information. The species outlined in *Section 4.2.2* are less well understood and have been the subject of additional research in the construction of this technical volume.

4.2.1 Priority species and risks

Whilst many potential nuisance species have been identified and included within the HR Wallingford dataset, they carry different risk levels, which alter with the type of power asset under consideration. The overall risk represents the impact of the hazard considered combined with the probability of occurrence. There is considerable variability in the probability of occurrence, both geographically and temporally. For example, exposed rocky shorelines with dense seaweed and kelp assemblages are more susceptible to storm damage and subsequent drifting debris than more sheltered sandy or muddy areas. Kelps are likely to be most dense during the summer and autumn storms and therefore are likely to produce more debris then than during spring storms after the quiescent growth during the winter. However, seaweeds such as fucoids frequently retain their mass through the winter and storms in January and February can break significant weights of weed which can impinge on screens. Clogging of screens by plant debris is also affected by the spring-neap tidal cycle, with the highest masses likely to be transported on the spring tides, although this is strongly influenced by wind strength and direction.

For water intake facilities, with debris screens, the moon jellyfish (*Aurelia aurita*) is known to provide considerable nuisance at certain times of the year (generally May to September) when the water temperature and plentiful zooplankton allow fast proliferation and growth of ***medusae***. These blooms are carried towards water intakes predominantly by currents but also by wind and waves. When this happens, the soft bodies of multiple animals can quickly clog the screens, requiring mechanical removal. Large numbers of small-bodied moon jellyfish, with a bell diameter of ~10 centimetres (cm), have a tendency to lead to worse clogging than smaller numbers of large medusae.

A high priority species for all types of power asset is the blue mussel (*Mytilus edulis*) and its closely related species, the Mediterranean mussel (*Mytilus galloprovincialis*). Both species can disperse considerable distances, although the Mediterranean mussel is more limited in terms of temperature. Strong ***byssal thread*** attachments, strong shells and a fast growth rate mean that these molluscs have provided considerable nuisance to structures by both fouling and clogging mechanisms. In confined areas, dosing with chlorine can minimise settlement and development of the larvae, which is most probable during their active larval dispersion months of April to September. Many assets are too exposed for such control mechanisms and instead must instigate mechanical cleaning regimes to ensure that structural stresses are kept within engineering tolerances.

Other species which settle with hard calcareous shells, such as barnacles (*Balanus* species, *Austrominius modestus* and *Chthalamus stellatus*) or tubeworms (*Pomatoceros triqueter, Hydroides elegans* and *Filograna implexa*), are highly resistant to being dislodged. Treatment options are as for mussels, discussed above. Barnacles can settle year-round, whilst tubeworms are more likely to settle during larval dispersion months. Information regarding the larval stages of these animals is patchy, with more information available on the barnacles than the tubeworms.

Kelps (particularly *Laminaria digitata* and *Laminaria hyperborean*) are large algae, with plants capable of growing to metres in length, and up to 30 cm across the blade (flat section). They are also amongst the fastest growing plant species on Earth, capable of growing around a metre in length in a month. This means that during their growing season, which tends to be through spring and summer (April to September), they can produce considerable biomass. They are also able to regenerate quickly if the blade is broken or torn away, and free-floating blades following storms can be a major component of vegetation mats which are a major hazard to clogging intake screens. No control mechanisms are available to reduce vegetation mats and thus mechanical cleaning is the only recourse for screens clogged by such mats.

Table 4 summarises the seasonality and geography of the priority species discussed above.

Table 4. Seasonality and geography of priority species.

Species	When most likely to occur	Where most likely to occur
Moon jellyfish	May to September	Assets in or exposed to open sea areas
Blue mussel	April to September	All areas
Barnacles	Year round	All areas
Tubeworms	Unknown, but expected to be spring/summer	All areas, but more in south of area
Kelps	April to September, spring tides, stormy weather	West coasts

4.2.2 Other species of interest

Due to the hazard they pose, the higher priority species have been well studied; this means that information for mussels and kelps is available for most of the parameters investigated. For the lower priority species, the availability of information was patchier. Good information has been found for all parameters for fish species and distributions of all species. Information about depth preferences, minimum tolerable salinities, maximum life expectancy and preferred substrate was found for most species. However, for parameters like nutritional or temperature triggers, information was found for only a selection of species. Whilst information on spawning period, expected larval persistence and the potential larval or propagule dispersion distance was found for most species, factors governing larval behaviour — such as mobility and settling velocities —

were not found. It is possible that some of the missing information discussed below exists in other literature, but this section reflects the state of knowledge at the time of writing.

Generally, there is insufficient information on the life cycles of many of the identified species to be confident that the conditions which lead to nuisance proliferation are adequately described for the purposes of providing an accurate hazard assessment. Most priority species identified are principally hazardous in spring and summer, although some present similar hazard levels year-round.

Within the database, maximum growth rates have been recorded where discovered to provide the most conservative estimate. However, growth rates are generally dependent on the immediate environmental conditions where the flora or fauna are situated. For example, flora require certain levels of nutrients and light for optimum growth conditions and changes in those due to seasonal conditions will affect the speed of growth.

Larval observations are frequently those provided by laboratory experimentation, rather than under real-world conditions, which could mean that environmental factors other than those manipulated within the laboratory could also provide control or promotion of settling patterns. The formation of biofilms is one such factor. In particular, settling velocities for colonising species were difficult to discover. Often studies referred to related species, but not the exact species under consideration.

Very little information was found on nutritional triggers; although many of the jellyfish were linked to zooplankton availability, little was discovered that gave qualitative estimates of zooplankton concentrations. Likewise, nitrates and ammonia were linked to growth of seaweeds and kelps, but nutrient availability was considered complex, with other factors such as light, salinity and CO_2 availability. No definitive quantitative information on levels of nitrates or ammonia was discovered.

The HR Wallingford dataset should be considered as a snapshot of the information available at the time of publication (2016). The marine biological environment is inherently dynamic and future changes to water temperatures and circulation patterns, e.g. as a result of climate change, are expected to alter both native and non-native species distributions. As coastal and offshore industries continue to develop, it is hoped that their experiences of biofouling will add further information to the current dataset.

4.3 Hydrodynamic mechanisms

All of the problem species are mobile during at least part of their life cycle, but they have differing levels of autonomous motility and, as such, they are subject to somewhat different hydrodynamic mechanisms. Hydrodynamic mechanisms may be considered as the processes governing or governed by the motions of fluids (the fluid in this case being seawater). In the context of this report, the relevant mechanisms include tidal currents, wind and waves. The relative magnitude of each mechanism will vary in space and time, but site-specific generalisations, or patterns, can be predicted.

For seaweed, jellyfish and colonising organisms, the main hydrodynamic mechanism is currents, but these may be driven by a complex interaction of factors. The UK sits in relatively shallow waters, on the European continental shelf. The absence of deeper waters means that deep-ocean currents, which are driven by density and temperature gradients, are not significant around the UK. Instead, currents are largely driven by tidal cycles. For example, at Torness Power Station (south-east of Edinburgh), the tide reliably floods from the north and ebbs from the south (*SEPA, 2003*). Tidal velocities, the time of the tidal reversal, and the mean fetch over each tidal cycle can all be predicted with high accuracy. However, tidal currents are not vertically uniform throughout the water column (i.e. two-dimensional). The seabed creates friction, slowing down the current. Shear stress is then passed upwards, decreasing as it passes from layer to layer. Currents are therefore not vertically uniform, so the vertical distribution of seaweeds and jellyfish should be considered.

For seaweeds, vertical distribution is largely determined by their density relative to seawater. Different seaweed types will exhibit positive, negative or neutral buoyancy, meaning they tend to occur on the surface, seabed or anywhere between, respectively. However, even negatively buoyant material can be suspended by strong currents or wave energy. Furthermore, the buoyancy of different seaweeds can change, e.g. after ***stranding***, desiccation and ***re-suspension***. *Coughlan (2007)* observed that neutrally-buoyant and slightly heavier-than-water material (e.g. kelp stems and holdfasts) moved with the tide edge, with maximum quantities oscillating on the seabed about two or three waves behind the tide edge. This is a common phenomenon which can be explained by the backward and forward motions of the water (caused by the breaking waves above) being equal at the seabed — and thus trapping material (*Butt and Russel, 2002*) which can then be transported by other means.

Unlike seaweeds, jellyfish and the planktonic life stage of colonising organisms actively select their vertical position within the water column. Recent research has observed that jellyfish can make extensive vertical movements, up and down through the entire water column, dozens of times per day (*Hays et al., 2012*). This vertical movement behaviour is not fully understood but probably serves to maximise foraging success. It is therefore difficult to predict where jellyfish will occur vertically within the water column. However, this means that without further information, there is no advantage to considering three-dimensional hydrodynamic mechanisms for jellyfish transport.

The spring-neap tidal cycle may also be significant to marine ingress events. Spring tides move a greater volume of water, necessitating higher velocities and energy levels; this may be sufficient to mobilise material that may remain on the sea floor during neaps. Marine debris is often deposited on the coast during ebb tides, and re-suspended on subsequent flood tides. When debris is deposited during high spring tides, it may not be re-suspended until the next spring tide.

Although largely dominant around the UK, tidal currents will frequently be complicated by wind and/or wave-driven currents. Wind applies wind stress to the sea surface which, given sufficient duration and fetch, will create a wind-driven surface current. However, resistance of the sub-surface water layers creates substantial drag on the surface layer, such that the wind force, duration and fetch must be significant to create any residual current. For this reason, wind-driven currents are more likely to be significant on the west coast of the UK, where dominant south-westerly winds have a very long fetch. However, long fetches are possible elsewhere around the UK, depending on the wind direction. It should also be noted that wind-driven surface currents are possible even with a short fetch, given sufficient wind force and duration.

The Coriolis force causes any wind-driven current to flow at an angle to the wind (to the right of the wind in the northern hemisphere), and this angle increases with depth, creating a tapered 'Ekman spiral' where the residual current both reduces in velocity, and turns further to the right, as depth increases. Again, this is important because seaweed and jellyfish may occur at specific heights within the water column. Where material, e.g. buoyant seaweeds such as bladderwrack (*Fucus vesiculosus*), sits above the water surface, any wind will apply a direct pushing force upon on the weed, as well as significantly increasing the wind stress on the sea surface layer.

On the open seas, waves generally transport energy rather than material; but breaking waves, and even non-breaking waves if they are in shallow water, do move material. In open water the effect of waves is likely to be small compared to that of tidal and wind-driven currents.

However, waves breaking at the shoreline release their energy which may drive longshore drift. This can work either in combination with (i.e. increasing), or against (i.e. reducing) the net effect of the tidal current. Breaking onshore waves also create rip-currents, where the water from the breaking waves is transported back offshore. As previously mentioned, there will inevitably be a point in space where the backward and forward motion of the waves is equal. This effective isolation from cross-shore forces allows material to collect, from where it can then be transported by other means such as longshore drift and tidal currents.

Anthropogenic activities are not conventionally considered to be hydrodynamic mechanisms, but international shipping does move water masses from one place to another when taking on, and subsequently releasing, ballast water. This process is relevant to this report when those masses also transport the planktonic life stages of clogging or biofouling alien species. In their inventory of clogging and biofouling species, HR Wallingford identifies seven, from the total of 62 species, as invasive. Invasive or alien species can also be introduced via the conventional hydrodynamic mechanisms previously discussed, either within the water column during their planktonic life stage, or after settling on marine debris.

Material causing marine ingress in the UK may be summarised into three categories: seaweed (in its broadest sense — sea 'weed'), plankton (which includes jellyfish and ctenophores) and fish. The fish species responsible for significant marine ingress events are highly mobile, and not significantly affected by the short-term hydrodynamic mechanisms discussed here. For seaweed and jellyfish, tidal currents are the main hydrodynamic mechanism leading to marine ingress in the UK, but wind- and wave-induced currents, as well as waves themselves, are contributory factors. Currents are not vertically uniform, so the vertical zonation of seaweed and jellyfish, within the water column, is an important factor governing their transportation. This is simpler to predict for seaweed than for other species, e.g. jellyfish, which can actively select their vertical position.

Hydrodynamic mechanisms will be considerably more complex at some sites than others. To understand the hydrodynamic mechanisms for a specific site, it is recommended to investigate:

- tidal currents, e.g. using Admiralty charts available from *Admiralty (2018)*;
- the effect of wind and waves upon the tidal currents; and
- the development of a 2-D or 3-D hydrodynamic model.

4.4 Developing mitigation strategies

Once an assessment has been made as to the species that will affect infrastructure at a particular site and the hydrodynamic mechanisms that may lead to marine biofouling events, it is necessary to develop a mitigation strategy. The type of mitigation scheme will vary greatly depending on the species and asset under consideration. It is not a focus of this technical volume as it is not explicitly characterising the hazard, but a couple of examples are provided below.

A common mitigation strategy is the use of biofouling-resistant paints and chemicals to stop the initial build-up of marine matter. These coatings often have to be reapplied on a regular basis, which makes them infeasible for certain types of infrastructure. An example use of antifouling coatings is detailed in Section 2.1.2 of Case Study 3 – Hunterston, and more information about the regulations concerning anti-fouling paints and coatings is provided in *Section 6*.

Certain types of marine biofouling species have been the recent focus of research projects on remote sensing. The idea is to use different remote sensing techniques (e.g. unmanned aerial vehicles, satellite) to provide an early warning system for potential marine biofouling events. In this way, infrastructure owners and operators are provided with additional information ahead of an event which may cause a risk to infrastructure, which allows them to take preventative measures.

Site-specific examples of mitigation strategies are outlined in more detail in Case Study 2 – Dounreay and Case Study 3 – Hunterston.

4.5 Other studies and projects

A selection of other projects have investigated the impact of nuisance species on power assets; a brief summary of some of these projects is provided below.

One of the most prominent projects is the EU VECTORS programme. *VECTORS (2015)* states that "VECTORS seeks to develop integrated, multidisciplinary research-based understanding that will contribute the information and knowledge required for addressing forthcoming requirements, policies and regulations across multiple sectors. It aims to elucidate the drivers, pressures and vectors that cause change in marine life, the mechanisms by which they do so, the impacts that they have on ecosystem structures and functioning, and on the economics of associated marine sectors and society". The programme ran over four years, from 2011 to 2015, and provided greater insight into some biological hazards with a focus on the Mediterranean Sea area. The need for further research was highlighted; in particular there are few long-term datasets on jellyfish occurrence, and a lack of rigorous evidence regarding whether anthropogenic changes to the marine environment have contributed to the perceived increase in jellyfish outbreaks.

The Marine Conservation Society (MCS) has a long-established observation programme for jellyfish, to attempt to further understand their seasonal distribution, and has amassed a database of information (*MCS, 2017*). Additionally, there have been initiatives from British academic organisations to map jellyfish distributions from aerial surveys (*Doyle et al., 2007; Houghton et al., 2006*).

The Global Invasive Species Programme ran from 1987 until 2011, producing a database of invasive species, including information on their biofouling potential. The programme was terminated due to lack of funding, but the database and guidelines are still accessible at *ISSG (2018)*.

The EU Options for Delivering Ecosystem-Based Marine Management (ODEMM) project provides tools and techniques to aid management decisions that promote sustainable use of the marine environment (*ODEMM, 2018*). The project ran from 2010 to 2014 and was a consortium of 17 project partners across Europe's four regional seas — the Baltic Sea, the Black Sea, the Mediterranean Sea and the North East Atlantic Ocean.

5. Related phenomena

There are no specific minor phenomena associated with marine biological fouling as outlined in this technical volume. It is possible that marine biological fouling could occur in combination with other phenomena, although little information is currently available on this topic. For more general information on natural hazard combinations see Volume 12 — Hazard Combinations.

In this section, specific guidance is provided on regulatory instruments, codes and standards applicable to the marine biological fouling hazard. For more information on general regulatory considerations, please see Volume 1 — Introduction to the Technical Volumes and Case Studies.

There are currently no legal instruments directly regulating marine biofouling or biological clogging. However, there are regulations which apply to the use of anti-fouling paints and coatings, e.g. the International Convention on the Control of Harmful Anti-fouling Systems on Ships. These paints and coatings have been known to leach slowly into seawater, where they can persist, killing sea life, harming the environment and possibly entering the food chain. The introduction and spread of invasive non-native species is also being dealt with by emerging and existing UK and EU legislation, e.g. EU Regulation 1143/2014 on Invasive Alien Species. In the UK, the Wildlife and Countryside Act 1981 (WCA) is the principal legislation dealing with non-native species.

In response to the potential hydrodynamic, structural and operational impacts due to long-term biofouling accumulation, engineering standards and guidelines have been developed for the more established offshore industries, such as oil and gas and shipping; e.g. Norsk Sokkels Konkuranseposisjon (NORSOK) standards (*Standard.no, 2018*). Many of these standards are now being applied within the growing offshore wind and marine renewable energy industry, to regulate how marine growth is accounted for in the engineering design and maintenance of structures. Such standards include that of Det Norske Veritas (DNV) for the design of offshore wind turbine structures (*DNV, 2014*) which is primarily used for UK offshore wind farms. This technical volume advises that marine growth should be taken into account by increasing the outer diameter of the support structure in the calculations of hydrodynamic wave and current loads. The thickness will depend on the depth below sea level and assessed based on local experience and existing measurements, although site-specific studies may be necessary (*DNV, 2014*).

Other examples include the International Organization for Standardization (ISO) 19901 and 19902 standards which provide some general considerations on marine growth. In ISO 19902, which focuses on fixed steel offshore structures for the petroleum and natural gas industries, it is advised that the anticipated mass of marine growth should be included when considering the dynamic model of any structure. In addition, components with circular cross-sections shall be classified as either 'smooth' or 'rough' depending on the amount and size of marine growth expected to have accumulated at the time of a loading event. Structural elements can be considered hydrodynamically smooth if located above highest astronomical tide (HAT) or sufficiently deep below the lowest astronomical tide (LAT). Site-specific data are required to reliably establish the extent of hydrodynamically rough zones (*ISO, 2007*). Typical values for hydrodynamic coefficients for the rough and smooth cases are given in *Table 5*.

Table 5. Typical effects of biofouling on hydrodynamic coefficients (ISO, 2007).

Surface component	Drag coefficient	Inertia coefficient
Smooth	0.65	1.6
Rough	1.05	1.2

Some standards advise that marine growth should be taken into account as appropriate for the location of the structure. However, detailed information on marine growth extent at specific geographic locations is poor. Guidelines tend to relate to the latitude of the installation, for example south and north of 59°, and are often based solely on data from the North Sea. For example, the NORSOK standards provide values for the thickness of marine growth for latitudes 56°N to 59°N if no more detailed values are available (*Table 6*). The standard also states that the thickness of the marine growth is assumed to increase linearly to the given value over the first two years after installation. These values are reflected in the most recent version of the DNV standard (*DNV, 2014*) which also includes some recommended thickness measurements for the Norwegian Sea (*Table 7*).

Table 6: Marine growth thickness recommended by NORSOK for latitudes 56°N to 59°N.

Water depth (m)	Marine growth thickness (mm)
Above +2	0
+2 to −40	100
Below −40	50

Table 7: Marine growth thickness recommended by DNV (2014).

Depth below MWL (m)	Marine growth thickness (mm)	
	Central and northern North Sea (56° to 59°N)	Norwegian Sea (59° to 72°N)
−2 to 40	100	60
>40	50	30

The decommissioning of wind turbines in the Solway Firth (UK) allowed photographs to be taken of the marine growth that had accumulated since their installation in 2009 (*Figure 4*). Hard fouling of up to 300 mm thickness was observed in the upper 2 to 3 m of the submerged structure. It was concluded that an expected marine growth thickness of 100 mm up to 40 m depth outlined in the DNV Standard (*DNV, 2014*) is overestimated. Although some areas exceeded the 100 mm thickness value, this was found to be only in the top 3 m, and the remainder of the structure had minimal growth.

Figure 4. Decommissioned wind turbine showing hard fouling of the upper 2 to 3 m of the submerged structure.

As the offshore wind industry expands and becomes more established, more biofouling information for different geographic regions has become available. In light of this, DNV is updating its standards (*DNV, 2014*) accordingly by providing guidance notes advising developers to expect greater marine growth thickness in warmer waters and to consider this in their engineering design. Since marine growth represents an increase in the total mass, it can potentially lower the natural frequency which should also be taken into account. Also, as marine growth has a higher specific gravity than seawater, it is expected to increase the dead load on offshore structures (*Fevåg, 2012*). However, *Heaf (1979)* suggested that in terms of the total weight, the submerged weight of the marine growth is insignificant for representative oil and gas platforms. Nevertheless, the need for location-specific guidance for marine growth prediction at a higher resolution is still required and will hopefully be possible as more data become available from different wind farm sites.

The HR Wallingford database collates information on marine and coastal species which are known, or considered likely, to cause a biofouling hazard in the North Sea and European Atlantic waters. However, this work should be considered as a snapshot of the information available at the time of publication of the database (2016). The marine biological environment is inherently dynamic and future changes to water temperatures and circulation patterns (e.g. as a result of climate change) are expected to alter both native and non-native species distributions. Various observations have been made with respect to previously more southerly distributed species gradually extending their ranges northward as sea temperature averages increase; the Mediterranean mussel is one such species. Currently, it appears that jellyfish blooms are becoming more frequent and the factors behind this, whether natural, attributed to climate change or other anthropogenic influences, are being further investigated elsewhere.

Alien species (i.e. non-native species that have become established within the area in sufficient numbers to cause detrimental effects) are included within the HR Wallingford dataset. Some have already caused nuisance within their new ranges, or are a known hazard in their native territories. These established species are able to successfully colonise, breed and proliferate within the area. From the full species dataset identified, those which are considered to be non-native invasive species are:

- stalked/leathery sea squirt (*Styela clava*), within Ascidea group;
- slipper limpet/boat shell (*Crepidula fornicata*), within Mollusca group;
- Wakame seaweed (*Undaria pinantifida*), within Algae group;
- japweed/wireweed (*Sargassum muticum*), within Algae group;
- warty comb jelly/sea walnut (*Mnemiopsis leidyi*), within Scyphozoa group;
- tubeworm (*Hydroides elegans*), within Polychaeta group;
- Australasian barnacle (*Austrominius modestus*), within Crustacea group.

It should be recognised that there is potential for further alien species to become established in the future, but it is outside the scope of this project to forecast which species might be liable to colonise these waters in the future in response to alterations in environments. Climate change could cause such alterations, with temperature change being one of the main parameters expected to facilitate establishment. However, the introduction of alien species to the coastal and marine environment is now being addressed elsewhere, with the nuisance that such species represent being recognised. Some of the measures now being implemented are:

- ballast water arrangements for shipping, such as the International Maritime Organisation (IMO) International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004;

- controls on removing fouling organisms from vessels, with any debris needing to be collected and responsibly disposed; and
- importation of marine organisms being more strictly controlled, e.g. the slipper limpet was inadvertently introduced to European waters with the culture of imported American oyster species.

Alien species, nonetheless, have other pathways of invasion, one being the colonisation of floating debris including plastics, and any changes to ocean water currents as a result of climate change could also allow further nuisance species to establish (*Stelios et al., 2013*).

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Arborescent
Resembling a tree.

Assemblage
A collection or gathering of items.

Benthic
Associated with, or occurring on, the sea floor.

Biofilm
Created when microorganisms adhere to a surface and to each other. The microorganisms excrete extracellular components (e.g. polysaccharides, proteins and DNA), resulting in a slimy matrix.

Bryozoans
Colonies of microscopic animals; the colonies of different species take different forms.

Byssal threads
A bundle of filaments, secreted by many species of bivalve mollusc (e.g. mussels) to attach themselves to surfaces.

Calcareous
Composed of, or containing, calcium carbonate, calcium or limestone.

Ctenophores
Marine invertebrates constituting the phylum Ctenophora, also known as comb jellies, sea gooseberries or sea walnuts. Superficially similar to jellyfish.

Diatoms
A major group of microorganisms found in the oceans.

Epiphytes
Organisms that grow on the surface of plants.

Hydroids
Colonies of microscopic animals (polyps, or inverted jellyfish) attached to a feather-like base, often mistaken for plants.

Macroalgae
Seaweed.

Macrofouling
The attachment of larger organisms such as barnacles, diatoms and seaweed.

Mean low water (MLW)
The average water level between low tides at springs and neaps.

Medusae
The free-swimming life stage of a jellyfish, typically having an umbrella-shaped body with stinging tentacles around the edge.

Microfouling
The formation of a biofilm.

Motile
The ability of an organism to move independently, using metabolic energy.

Once-through cooling water system
Extracts cold water from the environment, circulates it through pipework and condensers to absorb heat from other systems, e.g. steam turbines, and then discharges the warmed-up water back to the environment. The opposite of a closed system, in which the water is recirculated.

Propagule
A general term for any structure (e.g. spores) that functions in propagating an organism to the next stage in its life cycle, such as by dispersal.

Re-suspension
Material, previously deposited by an outgoing tide, picked up again by the incoming tide.

Sessile
Fixed in one place; immobile.

Stranding
Left ashore after the tide has receded.

Substrate
The surface or material on which an organism lives and grows.

Abbreviations

DNV	Det Norske Veritas
EPS	Extracellular polymeric substances
HAT	Highest astronomical tide
ICES	International Council for the Exploration of the Sea
IMO	International Maritime Organisation
IOS	International Organization for Standardization
ISSG	Invasive Species Specialist Group
LAT	Lowest astronomical tide
MCS	Marine Conservation Society
MLW	Mean low water
ODEMM	Options for Delivering Ecosystem-Based Marine Management
SEPA	Scottish Environment Protection Agency
WCA	Wildlife and Countryside Act 1981

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