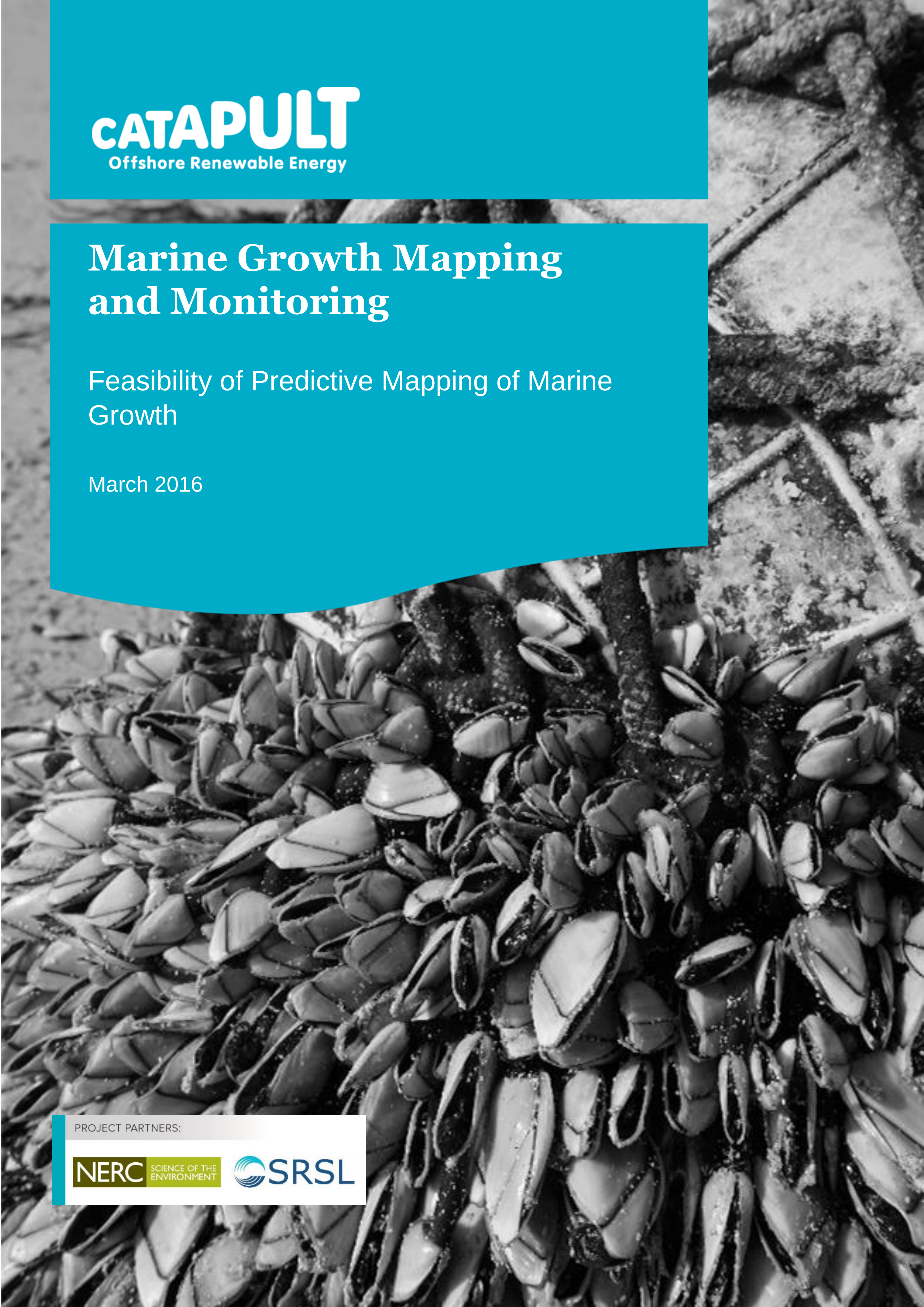

CATAPULT
Offshore Renewable Energy

Marine Growth Mapping and Monitoring

Feasibility of Predictive Mapping of Marine Growth

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Executive Summary

Any hard structure submerged in the sea will eventually host a community of marine organisms growing on and associated with its surface. This marine growth, or biofouling, is comprised of a variety of species depending on the location, depth and configuration of the structure. Marine growth on renewable energy devices can have consequences for structural integrity, hydrodynamic efficiency, and survivability of devices, and may also encourage the establishment and growth of non-native or invasive species.

In 2015, the Offshore Renewable Energy Catapult commissioned a feasibility study to evaluate options for mapping and monitoring marine growth on renewable energy structures. This feasibility study comprised three parts:

1. *Industry consultation* [1]– to provide insight into industry issues associated with biofouling, to which 15 responses were received
2. *Feasibility of Predictive Mapping of Marine Growth* – a study reviewing key biofouling species and their implications for renewable energy structures and the feasibility of developing a predictive mapping tool for marine growth
3. *Feasibility of Sensor Development for Monitoring Marine Growth* – a study reviewing promising technology options for the development of a marine growth sensor, designed to provide information about marine growth on a structure in real-time.

This report presents the outcomes of the second element of this project, mapping marine growth.

Legislation and guidelines for marine growth

Different types of standards, guidelines, and legislation regulate the control of marine growth communities on offshore structures. Marine industry standards and guidelines in place for biofouling include those provided by Det Norske Vertitas, British Standards Institute, and the International Organisation for Standardisation. Often, these are based on data derived from the North Sea, and are not tailored to specific locations or regions. Few regulations specifically deal with the marine renewable energy industry. Furthermore, in light of recent EU and UK legislation[2][3][4] marine renewable energy developers may need to demonstrate that 'reasonable steps' have been made to prevent non-native species entering and/or spreading in UK waters, including those which are often found in biofouling assemblages.

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[1] Industry Consultation Report on Biofouling (2015), produced for the Offshore Renewable Energy Catapult by PML Applications Ltd., SRSL, and Akzo Nobel. 29 pp.

[2] EU Regulation 1143/2014 on Invasive Alien Species

[3] EU Marine Strategy Framework Directive (EC Directive 2008/56/EC)

[4] Wildlife and Natural Environment (Scotland) Act 2011

Industry concerns associated with marine growth

The industry consultation indicated that key concerns associated with the development of marine growth were: biofouling mass, thickness, surface roughness, heat transfer properties, corrosion, and impacts on wet connectors. In exposed locations occupied by wave and tidal energy devices, the growth of biofouling may be more rapid than in other, less exposed locations. Marine growth can alter the weight of structures considerably. The weight of biofouling acting on a structure is dependent on the volume of biofouling and the relative proportions of hard, dense species and soft, less dense species. While effect thresholds for biofouling mass on devices are presently hard to define, understanding the weight, weight in water, and density of biofouling associated with biofouling mass are highlighted as important knowledge gaps to be filled to support engineering decision making.

Marine growth serves to increase the effective diameter of structural components, with potential to alter structural drag and added mass coefficients. The thickness of marine growth is strongly related to the effective diameter of components, and will be influenced by species composition and growth rates, which are in turn influenced by location-specific environmental characteristics. As marine organisms begin to colonise the surface of a newly deployed device, surface roughness will increase, with implications for device efficiency, drag coefficients, and added mass coefficients. Surface roughness will also be influenced by species composition and growth rates in a location-specific manner

Biofouling species of concern

Submerged structures at locations characterised by different environmental conditions tend to host different dominant species. Neutrally-buoyant kelp are unlikely to exert additional weight on their host structure, but are more likely to influence structural drag and to cause structural abrasion. Blue mussels are a dominant component of ‘hard’ biofouling on shallow submerged structures, and can exert substantial weight on submerged structures, in addition to increasing the effective diameter and roughness of structures. Barnacles are a further element of ‘hard’ fouling and can contribute increased structural mass, component size and roughness. Barnacles can tolerate higher current speeds and wave exposure than kelp and mussels, and therefore may be a dominant fouling species on marine renewable energy devices in some locations. The difference between ‘soft’ (e.g. kelps) and ‘hard (e.g. mussels and barnacles) biofouling is crucial to nearly every issue or concern associated with marine growth highlighted by the marine renewable energy industry[1].

Environmental predictors of marine growth

Mussel-, kelp-, or barnacle-dominated communities are likely to be prevalent on different types of marine renewable energy devices at different locations, dependent on a number of physical and environmental parameters and how these interact with the ecological life history traits of the biofouling organisms. Kelp do not flourish in turbid waters due to light limitation impacting photosynthesis and growth, and will be limited to near-surface components. Mussels, on the other hand, are successful in turbid waters, especially where flow rates are increased, due to increased filter feeding potential Mussels tend to form dense aggregations on structures down to approximately 30 m in depth, beyond which barnacles begin to dominate. However, factors governing the relative dominance of barnacles or mussels are complex, and vary according to environmental and geographical factors.

In addition to device-specific structural considerations, environmental parameters such as seawater temperature, salinity, food availability, current velocity, and wave exposure have been identified as important in predicting the level of marine growth likely to occur on offshore renewable energy structures. Numerous datasets incorporating these characteristics are available, but there are challenges associated with selecting appropriate datasets for development of a predictive spatial map or model of biofouling.

Recommendations for future study

A thorough understanding of the environmental parameters which influence the development of marine growth could enable the development of relationships which predict the type and extent of biofouling on marine renewable energy devices on a geographical basis. Ultimately, these relationships could be applied to an industry-ready tool to map marine growth around the UK.

Perhaps the greatest challenge to the development of such a map is the availability of quantitative biological datasets relevant to biofouling communities, which will be necessary for both development and validation of any predictive relationships. In response, it is recommended that an industry-specific protocol for collecting information about biofouling be developed, alongside a central database to enable data management and access.

A mapping tool for marine growth could then be iteratively developed, incorporating more and more quantitative data as it accumulates within the database. A first step in doing so would be to develop robust statistical relationships enabling the prediction of potential biofouling composition from environmental parameters. These relationships will need substantial validation in order to achieve a sufficient level of confidence for use by the industry. The ability to predict biofouling composition, however, must be complemented by an improved understanding of how that composition relates to key engineering metrics such as weight and surface roughness. This will enable translation of information about biofouling composition to real applications within the marine renewable energy industry. Each of these components feeds into the development and maintenance of a marine growth mapping tool which could be broadly applied across the marine renewable energy and other offshore industries.

1 Development of Marine Growth Mapping

1.1 About this study

The necessary positioning of offshore renewable energy developments in marine environments characterised by strong tidal velocities and/or large waves presents several challenges to developers wishing to operate in these locations. Historically, such environments have also challenged scientists wishing to study the hydrodynamics, geology, and ecology of these sites, meaning that baseline environmental information is not always readily available to predict the potential impacts of the environment on operational devices, nor the potential impacts of operational devices on the environment.

The Offshore Renewables Joint Industry Programme for Ocean Energy (ORJIP, http://www.orjip.org.uk) is beginning to address some of these challenges for marine energy, focussing on those associated with environmental consenting. By providing information and support to the industry, this initiative aims to streamline and facilitate further UK development within the offshore renewable energy industry.

In the context of marine growth[5], the ORJIP lists both ‘reef effects’ and the ‘introduction of non-native invasive species’ as potential consenting issues for ocean energy projects in their Forward Look document (Aquatera Ltd. and MarineSpace, 2015). Marine growth is not yet considered to be a key strategic consenting issue for the marine renewable energy industry by regulatory bodies. It is, however, an important consideration for device developers and operators concerned with structural integrity, hydrodynamic efficiency, and survivability of their devices, and was the focus of a joint industry-academic workshop supported by the Natural Environment Research Council (NERC) at the 2012 Environmental Interactions in Marine Renewables conference in Orkney, UK.

In response to the 2012 workshop and the growing industry awareness of marine growth, Offshore Renewable Energy Catapult commissioned this project aiming to explore the feasibility of developing a marine growth mapping tool, allowing interested parties to predict the likely characteristics of biofouling communities at a given location, so that their associated effects on structures can be better understood. Such a tool could facilitate early decision making for project developers at the structural design and planning stages of a project, reducing later operational risks.

Recent advances in marine ecological research and GIS capabilities have allowed scientists to start to predict which species will inhabit particular habitats in the marine environment. These predicted interactions are based on environmental conditions such as wave energy, currents, temperature, nutrient concentrations, and salinity (Burrows et al., 2009; Burrows, 2012). This

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[5] Marine growth is also termed, ‘biofouling’, which refers to the undesired accumulation of biological material on man-made structures. Note that numerous terms are used to describe the growth of marine organisms on man-made structures, and in this report we use the terms ‘biofouling’, ‘fouling’ and ‘marine growth’ interchangeably in this context.

feasibility study seeks to establish whether similar techniques could be used to predict the characteristics of biofouling communities on offshore renewable energy installations. Such information, provided via an interactive tool, would allow operators to access location-specific guidance on device coating specification, drag effects, and maintenance intervals, and could potentially inform forecasts of asset management costs.

The high-energy environments where renewable energy devices are situated are challenging to work in, both for industry project developers and marine ecologists, leaving a substantial gap in ecological knowledge and understanding of biofouling communities in these locations. Preliminary insight into industry issues associated with biofouling was provided via an industry consultation[6], to which 15 responses were received from wave and tidal energy developers, test centres, and standards agencies. Following on from the industry consultation, a study was undertaken reviewing existing ecological publications, reports, and grey literature, focussing on biofouling communities and species and the physical and biological processes that could influence the characteristics of marine growth at offshore renewable energy sites. The results of this review are included within this report. In addition, the feasibility of developing a predictive biofouling tool and associated guidance is discussed, alongside an assessment of the availability of suitable datasets for geostatistical analysis to feed into the development of the biofouling tool. The current report is concluded with recommendations for the direction of future work in towards addressing knowledge gaps concerning the potential impacts of marine growth on marine renewable energy devices.

1.2 Why focus on marine growth?

Any hard structure in the sea, whether natural or man-made, will eventually host a community of marine species growing on its surface. Such growth can add weight, change the geometry and roughness of submerged structural elements. These changes will in turn influence the loading, dynamic response, and hydrodynamic efficiency of marine renewable energy technologies (Theophantos and Wolfram, 1989; Jusoh and Wolfram, 1996; Det Norske Veritas, 2013a). Marine growth can also influence corrosion rates, inspection accessibility and reduce the efficiency of heat transfer components. The severity of these effects is a function of the characteristics of biofouling material (i.e. mass, thickness, density and roughness) that is present on a structure at any given time. Such characteristics are in turn determined by the type of biofouling organisms present (species makeup) and extent of their growth.

Many marine renewable energy technologies will be deployed in coastal environments where typical biofouling characteristics are poorly understood. Furthermore, when compared to larger static structures such as monopiles associated with offshore wind, biofouling may have a disproportionately large effect on the mechanical performance of smaller dynamic elements typical of many marine renewable energy technologies. Therefore, it is important to consider the

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[6] Industry Consultation Report on Biofouling (2015), produced for the Offshore Renewable Energy Catapult by PML Applications Ltd., SRSL, and Akzo Nobel. 29 pp. *Available on request from the Offshore Renewable Energy Catapult, www.ore.catapult.org.uk*.

influence of biofouling at an early stage to take steps to minimise its impact on device performance.

To minimise issues associated with marine growth on structures, a long history of paints, coatings, and other protective measures have been tried and tested on marine structures. Many of these strategies have proven to be effective, while others have been abandoned because of the potential for environmental damage as a result of biocides and toxins.

Many of the species that make up marine fouling communities are also commonly found on natural rocky substrates. These 'natural' communities have been well studied, particularly in the UK, and a great deal of information exists regarding the life histories and environmental preferences of these species. Much of this knowledge base can be applied to biofouling communities, which are influenced by the similar physical, chemical, and biological factors to natural hard-substrate communities (Terlizzi and Faimali, 2010). Combined with historical studies of oil and gas platform fouling communities and a growing interest in the marine growth found on offshore wind turbines, there is increasing impetus to apply existing marine ecological understanding for industry benefit. This will allow a better understanding of how marine growth communities develop and whether or not their makeup can be predicted. The application of marine ecological knowledge may also provide insight into new, alternative strategies for reducing marine growth on man-made structures in the sea.

With a wealth of relevant, applicable ecological knowledge to draw on, examining potential issues associated with marine growth represents a 'quick win' for the marine renewable energy industry, as the implications of biofouling could be severe. Tools and techniques that could enable developers to better predict biofouling characteristics and account for potential effects at an early stage of project development could have positive impacts on project outcomes. Identifying the types of input data, industry-relevant output metrics, and potential pathways for development of one such tool is the focus of this study.

2 Legislation, regulations and common operational practise for marine growth

2.1 Introduction

Marine growth is an important consideration both from engineering and environmental perspectives. In response to the potential for marine growth to affect the hydrodynamic performance and survivability of offshore structures, engineering standards have emerged over time as offshore industries such as oil and gas and shipping have developed. Many of these standards are applied within the marine renewable energy industry. Marine growth has more recently been associated with species invasions, most notably within the shipping industry, but also as a consequence of installing man-made structures in the marine environment (Glasby et al., 2007). In response to the threat of invasive and non-native species, governments have developed widely applicable legislation at national and EU levels to prevent their establishment and spread, which must be adhered to by marine operators.

2.2 Industry standards for marine growth

Numerous industry standards are in place to regulate how marine growth is accounted for in engineering design and structural maintenance in the marine environment. Examples include Det Norske Veritas (DNV) standards for the design of offshore wind turbine structures, position mooring marine growth, and recommended practice on environmental conditions and environmental loads (Det Norske Veritas 2004; 2010; 2013a; 2013b). Further guidance can also be gleaned from other standards associated with the offshore oil and gas industry (BMT Cordah Limited, 2011; International Organization for Standardisation, 2007; British Standards Institute, 2005). The majority of standards are conservative and designed to protect property and ensure safety, meaning many engineers will need to consider biofouling more closely to optimise the performance of their device.

Many of the standards state that marine growth shall be taken into account as appropriate for the location of the mooring or structure. However, information relating the extent of marine growth to specific geographical locations or regions is poor. Guidelines tend to relate to the latitude of installation, for example, south of 59°N and north of 59°N, and are often based solely on data from the North Sea. Variability in fouling communities on the west coast of the UK may be greater, requiring location-specific guidance at higher resolution.

DNV has noted that these guidelines are tailored to installations in the North Sea, but intend to review them as more data become available from installations at other locations (Benson Waldron, DNV, *pers. comm.*).

2.3 Non-native alien species: environmental legislation and regulation associated with marine growth

Biofouling communities are of growing interest as artificial structures can encourage the growth of non-native species: a concern under emerging legislation within the UK. For example, under the Wildlife and Natural Environment (Scotland) Act 2011, it is now an offence to

- Release or allow to escape from captivity any animal to a place outwith its native range.
- Cause any animal out with the control of any person to be at a place outwith its native range.
- Plant or otherwise cause to grow any plant in the wild outwith its native range.

In essence, it is now illegal to accidentally transfer or spread a non-native ‘alien’ species as a result of inadequate biosecurity procedures and planning. Following on, companies may now be liable for the costs associated with eradication or control of an invasive non-native species, as well as for restoration of the environment.

At a European level, regulations regarding alien invasive species entered into force on January 1st 2015 (EU Regulation 1143/2014 on Invasive Alien Species), including the following mandate:

Target 5 – To control invasive alien species: By 2020, invasive alien species and their pathways are identified and prioritised, priority species controlled or eradicated, and pathways are managed to prevent the introduction and establishment of new alien invasive species.

This regulation focusses on both the marine and terrestrial environments and identifies particular species of European Union concern. Specific to the offshore marine environment, the EU Marine Strategy Framework (EC Directive 2008/56/EC) directive includes ‘*non indigenous species introduced by human activities are at levels that do not adversely alter the ecosystem*’ as one of eleven high-level descriptors of Good Environmental Status. Member states are now required to develop marine strategies within their own waters with regards to these eleven descriptors.

In response to this changing legislation, marine renewable energy developers may need to demonstrate that ‘reasonable steps’ have been made to prevent such species entering and/or spreading in UK waters. Guidance recommends the use of biosecurity planning to ensure best practice is being followed. Biosecurity plans are likely to require biogeographic information on the likelihood of spread and invasion as well as the socio-economic and environmental risks associated with key species (Payne et al., 2014). The provision of biogeographic information for biosecurity planning purposes could be a productive future development for a tool profiling biofouling around the UK, as is discussed in Section 9.6.

2.4 Common operational practice for biofouling mitigation on marine renewables structures

Approaches to dealing with marine growth vary within the marine renewable energy industry and across the wider marine engineering and operations field. The consideration of marine growth is an important step when designing marine structures to ensure appropriate design tolerances. Structural elements designed to account for additional structural loading due to marine growth can be incorporated at the early stages of the development process. These design considerations will require an understanding of biofouling growth characteristics (e.g. accumulation rate, weight, thickness, surface roughness). Operational maintenance plans often incorporate activities to scrape, clean, or remove biofouling from specific structural elements or from entire submerged structures across the life of a development. Location-specific understanding of biofouling characteristics may reduce the occurrence of additional, costly, unscheduled maintenance activities resulting from biofouling.

A range of marine protective and antifouling coatings are used on submerged components to reduce marine growth. The Reliable Data Acquisition Platform for Tidal (ReDAPT) project tested the efficacy of a suite of coatings in extreme conditions at the Fall of Warness in Orkney over a period of 24 months. Results indicated that both biofouling and corrosion rates were rapid at this site, and highlighted that selection of appropriate coatings could be a key consideration for ensuring the long term operation of tidal energy devices (Vance et al., 2014).

Cathodic protection is a further method used to control corrosion of structural components, but has also been demonstrated to enhance marine growth under certain conditions, most notably calcareous organisms such as barnacles (Eashwar et al., 1995; Mallat et al., 2014). For long term deployments, both cathodic protection and antifouling coatings will need to be carefully considered in the context of likely fouling species and the potential long term build-up of marine growth.

3 Industry concerns associated with marine growth

3.1 Introduction

An early phase to the current project involved liaising with various industry stakeholders in order to understand issues associated with biofouling and assess the extent to which concerns were common across technology types. The full report is available on request from the Offshore Renewable Energy Catapult, but a summary of the key findings are included below:

1. The effects of marine growth on submerged structures are a concern shared across the marine renewable energy industry. However, specific effects were varied and are often device- and component-specific
2. An improved understanding of relevant biofouling characteristics typical of renewable energy devices would better support future engineering decisions. Surveys of existing structures and devices were identified as the principal means of gathering biofouling characteristics data
3. Structural considerations

While structural features unique to specific wave or tidal energy devices will not be discussed here, useful information can be gleaned by characterising devices as floating or fixed, surface-piercing or completely submerged, and in relation to the depth of particular structural features of concern. It is possible that such general information could be considered in the development of a mapping tool to predicting biofouling community characteristics and associated implications for structures.

In sheltered locations, experiment results have revealed substantial differences in the biological composition of biofouling communities between floating and fixed structures. These differences were attributed to the presence or absence of an intertidal zone, or a ‘swash’ zone, as well as to varying levels of exposure to light (Holloway and Connell, 2002). Similarly, floating renewable energy devices could be subject to different fouling communities than surface-piercing fixed structures (Miller et al., 2013). Completely submerged structures are likely to harbour biofouling communities in keeping with other environmental conditions at that depth. For example, for structures anchored or fixed within the photic zone where light can penetrate sufficiently for marine plant growth, kelp may be a substantial component of the biofouling community, up to certain flow speeds, beyond which, the community may be dominated by mussels. Deeper in the water column, barnacles might become dominant, as demonstrated in the ReDAPT project, where coated panels deployed at 42 m depth were dominated by the barnacle *Chirona hameri* (Vance et al., 2014).

Surface orientation, rugosity, deployment duration, and coating selection are all likely to influence the makeup of biofouling specific to particular devices. However, these may be secondary determinants of marine growth characteristics after the well-defined environmental and structural characteristics described in the previous sections. Once reliable predictions can be made based broadly on environmental and general structural features, individual developments and devices could then be subject to a subsequent, more detailed examination of potential biofouling based on device specific features such as small scale architecture, maintenance intervals, and coatings.

4 Environmental datasets for prediction of biofouling

4.1 Introduction

Numerous datasets are potentially available for use in the development of a predictive map of marine growth characteristics on offshore structures. It is worth noting that some characteristics such as temperature, seawater pH, salinity, and water velocity can also affect the performance of antifouling coatings (Chambers et al., 2006) particularly for biocidal coatings. Key guidance from the ReDAPT project suggests that it is prudent to characterise the marine environment in question in advance of specifying coatings for marine renewable energy devices and associated structures (Vance et al., 2014). As such, the datasets profiled in the tables below may also have use beyond marine growth mapping, in the field of coating specification.

There are challenges, however, in selecting appropriate datasets for development of a predictive model for marine growth. Understanding the spatial and temporal resolution required is important, as data are available across a wide variety of resolutions, and in the form of observational and interpolated information. Where possible, spatial data such as temperature and salinity should be resolved at the scale of a development, on the order of 1 km to 5 km, or 1/20º. Refining the resolution of parameters over to spatial scales relevant to fouling communities provides adequate information to distinguish between development sites. Higher resolutions for parameters such as wave exposure and current speeds, where available, should be used.

Many of the environmental parameters highlighted in the previous section are temporally variable, often varying with seasonal cycles and larger scale inter-annual phenomena such as the North Atlantic Oscillation (Hurrell et al., 2003). In these cases, decisions must be made with regards to the temporal resolution of data used. For example, sea surface temperature datasets are available in various formats, from seasonal mean values, to annual averaged values, to longer-term averaged values. Minima and maxima at each of these temporal scales could also be used. Laminaria digitata distribution, for example, seems to be most strongly related to annual maximum sea surface temperature, rather than annual means or minima (Raybaud et al., 2013).

With this in mind, a selection of commonly accessed oceanographic, environmental, and biological datasets and data sources are described in Table 1.

Table 1: Available environmental and biological datasets of relevance to predicting marine growth

Data type	Dataset name	Description	Availability	Resolution
Various	ICES	ICES (International Council for Exploration of the Sea) hosts one of the largest repositories for observational marine datasets worldwide. Relevant datasets include CTD data and temperature/salinity measurements.	http://www.ices.dk/marine-data/dataset-collections/Pages/default.aspx	Varies, depending on number of observations available at a particular location.
Various	BODC	BODC (British Oceanographic Data Centre) hosts publicly accessible observational marine data. Relevant datasets include CTD data, temperature/salinity measurements, and wave data series.	www.bodc.ac.uk	Varies, depending on number of observations available at a particular location.
Various	MEDIN	MEDIN (Marine Environmental Data & Information Network) hosts UK-focussed marine datasets gathered by both public and private organisations. Relevant datasets include wave data series, currents, bathymetry, and observational oceanographic data.	Data availability varies by dataset. Publicly available datasets available for download at www.oceannet.org. Accessibility information and relevant contact details provided for other datasets.	Varies, depending on number of observations available at a particular location.
Temperature	HadISST	Met Office Hadley Centre Sea Ice and Sea Surface Temperature data set	http://www.metoffice.gov.uk/hadobs/hadisst/ in plain text and NetCDF formats	1° latitude, approx. 110 km, available globally
Temperature	OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis – daily analysis of current SST for global ocean.	http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html	1/20°, approx. 5 km

Data type	Dataset name	Description	Availability	Resolution
Temperature	ODYSSEA	Atlantic European North West Shelf Ocean – ODYSSEA Sea Surface Temperature Analysis – mean sea surface temperature at 1/20° resolution, from satellite data. Updated daily.	Available from the COPERNICUS Marine Environment Monitoring Service, www.marine.copernicus.eu	1/20°, approx. 5 km
Seawater optical properties	NEODAAS	Ocean colour data provided by the NERC Earth Observation Data Acquisition and Analysis Service. Includes high resolution chl a estimation from MODIS data.	https://www.neodaas.ac.uk/	500 m
Seawater optical properties	MODIS	Data from images from the MODIS Aqua satellite profiling chlorophyll a concentrations in mg/m3.	Available from the NASA Giovanni data portal as time-averaged, monthly values, at http: //disc.sci.gsfc.nasa.gov/giovanni/	9 km
Bathymetry	EMODnet	Digital Terrain Model bathymetry based on bathymetric surveys, composite data sets, and GEBCO 30” gridded data.	http://www.emodnet.eu/bathymetry	1/8 arc minute, approx. 200 m
Tidal power	UK Atlas of Marine Renewable Energy Resources	Values of depth-averaged tidal power and velocity for the UK, derived from a depth-stratified model based at NOC Liverpool.	www.renewables-atlas.info	1.8 km
Tides	DTU 10	The DTU National Space Institute offers a global ocean tide model developed from satellite altimetry measurements from the TOPEX/POSEIDON, Jason-1 and Jason-2 satellites.	http://www.space.dtu.dk/English/Research/Scientific_data_and_models/Global_Ocean_Tide_Model.aspx	0.125° × 0.125° grid cells, approx. 14 km

Data type	Dataset name	Description	Availability	Resolution
Wave energy	UK Atlas of Marine Renewable Energy Resources	Wave data generated from the Met Office UK Waters Wave Model, which covers the majority of the UK continental shelf. Includes archival results for hourly wave data for 7 years previous.	www.renewables-atlas.info	1/9° latitude ×1/6° longitude, approx. 12 km x 12 km
Wave data	ICOADS	The International Comprehensive Ocean-Atmosphere Data Set provides numerous types of marine data from the last three centuries provided as monthly summaries at a variety of resolutions.	http://icoads.noaa.gov	1° x 1° grid cells, approx. 110 km x 70 km for UK
Wave Fetch	Burrows 2012	Wave fetch data generated by M. Burrows at SAMS (Burrows, 2012), for the UK coastline.	On request from SAMS.	Up to 100m
Biology	NBN Gateway	The National Biodiversity Network hosts a large number of publicly available biological datasets, including the Marine National Conservation Review. Records of particular species and habitat can be downloaded individually. Datasets are available for most species, most commonly available as semi-quantitative recordings using the SACFOR abundance scale. For some species, data are available as ‘count’ data, or species presence/absence.	Available from the NBN Gateway at https://data.nbn.org	Dependant on number of observations available at a particular location.
Biology	SNH benthic species dataset 1993-2014	Species records from benthic surveys commissioned by SNH or partners where the outputs are under the custodianship of SNH. Additionally species records determined from SNH analysis of third party	Available from the NBN Gateway at https://data.nbn.org	Dependant on number of observations available at a particular location. Semi-

Data type	Dataset name	Description	Availability	Resolution
		commissioned benthic survey video footage are included. The dataset contains surveys which contributed to the Marine Nature Conservation Review (MNCR) programme, EU funded BioMar Life project, SNH Site Condition Monitoring including broad scale surveys in support of the Natura process, surveys to establish the impact of specific activities on marine habitats and species and surveys to support the Scottish Marine Protected Areas project.		quantitative data available in SACFOR abundance scale, otherwise as abundance or presence/absence
Biology	JNCC Marine Offshore Seabed Survey Data	Dataset containing information about offshore benthic species and habitats, and their location within the UK's marine area. Data collected from a variety of research vessels using a range of survey equipment including grabs, underwater video and still images, and benthic trawls. Post survey analysis has been conducted by various contractors to identify species and their abundances. Abundance is recorded as count, SACFORN, or presence/absence.	Available from the NBN Gateway at https://data.nbn.org	Dependant on number of observations available at a particular location. Semi-quantitative data available in SACFOR abundance scale, otherwise as abundance or presence/absence
Biology	ERI Biofouling species lists	The Environmental Research Institute holds lists of species found colonising settlement panels installed at renewable energy test centres across Europe.	Held at the Environmental Research Institute, UHI, and potentially available through the UHI MERIKA project –access will need to be negotiated.	Site-specific to renewable energy test centres.

Data type	Dataset name	Description	Availability	Resolution
Biology	SAMS National Lighthouse Board Buoy Fouling	SAMS holds species abundance data from a series of campaigns sampling biofouling on offshore navigation buoys in Scottish waters.	Available at SAMS	Scotland-wide, but site-specific to navigation buoy locations.
Biology	EMODnet	EMODnet aims to provide a single access point to European marine biodiversity data and products, including biomass, abundance, and gridded abundance. Species groups include macro-algae and invertebrate bottom fauna. However, No layers exist for *C. hameri* or *L. digitata*.	http://www.emodnet.eu/biology	Dependent on data availability.

5 The feasibility of predicting marine growth from environmental datasets

5.1 Introduction

Marine ecologists have demonstrated that the makeup of intertidal and subtidal communities on natural surfaces is in many cases broadly predictable based on key environmental characteristics such as wave exposure, sea surface temperature, and chlorophyll concentrations (Burrows et al., 2008; Burrows, 2012). Theoretically, it should be possible to develop similar relationships between certain types of biofouling communities and environmental characteristics in order to map marine growth around the UK, provided that adequate environmental and ecological datasets upon which to base such a model are available. Once such relationships are developed, they could then be applied to a spatial model within a GIS system.

5.2 Availability of relevant biological and environmental datasets

Numerous relevant environmental datasets are publicly available at adequate resolution (Table 1) for integration into this type of statistical mapping study. There is precedence for use of these environmental data, as has been previously demonstrated in several marine ecological studies (Burrows et al,. 2008; Hawkins et al., 2009; Burrows, 2012; Mieszkowska et al., 2013). The acquisition and use of appropriate biological data may be a more substantial challenge. In previous studies, the relationships developed for natural environments were based on robust ecological datasets. For example, the UK's intertidal rocky shores are well understood and have been well studied over the past century, and reliable biological distributions are available for most key species. Subtidal communities are historically less well studied, but the UK's Marine Nature Conservation Review (MNCR) project has produced a high quality dataset of subtidal species abundances at locations around the UK coastline using standardised measurement methodology. This has allowed for quantitative assessment of the relationships between species distributions and local and regional environmental characteristics (e.g. Burrows, 2012). As described in Section 7.7, however, structural differences between natural and artificial habitats mean that relationships developed for subtidal communities may not be applicable to marine growth on artificial structures such as marine renewable energy devices (Holloway and Connell, 2002).

At present, publicly available biological datasets characterising offshore renewable energy device biofouling communities are rare, and standardised quantitative species abundance data are even more so. Some quantitative evidence can be gleaned from studies of oil and gas platforms and offshore wind energy installations (e.g. Forteath et al., 1982; Langhamer et al., 2009; Mallat et al., 2014), but these structures are unlikely to be subjected to the same degree of environmental stress (wave energy and tidal currents) as marine renewable energy devices.

As projects develop and more devices are installed, and as discussions around device fouling become more common, anecdotal evidence describing biofouling community composition is beginning to emerge with growing industry experience. This could form the basis of preliminary semi-quantitative relationships. Within the academic community, researchers are working to quantitatively characterise biofouling communities on and in the vicinity of wave and tidal energy devices. For example, the Environmental Research Institute, University of the Highlands and Islands, in Thurso are working to deploy settlement panels at wave energy test centres across Europe, to characterise biofouling and potential invasive species at each location (Dr. Jennifer Loxton, *pers. comm*). A dataset also exists characterising the fouling communities of navigation buoys deployed in a range of flow environments (from high to low) around the west coast of Scotland (Macleod 2013b; Macleod et al. *in press*), while the ReDAPT project has provided specific insight into potential fouling at the EMEC Fall of Warness test site (Vance et al., 2014).

While these biological data can provide a loose guide for developing the necessary predictive relationships between environmental characteristics and biofouling species makeup, a wider set of survey data obtained using consistent methods and with wide geographical scope would substantially improve the predictive ability of such relationships. One feasible approach to this challenge is to develop a standardised industry methodology or protocol for recording biofouling on installed devices, which could sit within existing operational activities. Metrics must be easily identified by an operator, and might include items such as dominant fouling type (e.g. barnacles/mussels/kelp/other), depth, and thickness, assessed in a simple, but standard way. While this might allow developers to track and better understand their own biofouling issues, if compiled into a central database, such information would form an important resource for future biofouling mapping and development of associated guidance. Such information could be incorporated into a wider database for wave and tidal energy projects, similar to the SPARTA database for offshore wind energy projects (see https://www.sparta-offshore.com). The development of such a protocol for data collection and of a complementary anonymised database might be the first task of an initiative taking this mapping study forward from the feasibility stage.

A further approach to this challenge might include the deployment of settlement panels at planned offshore renewable energy leasing sites around the UK coastlines across all seasons and in a variety of energetic environments to validate industry data gathered via the protocol described above. While inherently resource intensive, such a study could be achieved as a partnership between Scottish, English, Welsh, and Irish institutions.

5.3 Developing statistical relationships from available datasets

Given that information on biofouling from the extreme environments occupied by marine renewable energy developments is limited, the development of a map should be approached in two or three stages. First, using the wealth of biological data from ‘natural’ habitats (e.g. rocky shores and rocky subtidal habitat) and appropriate environmental datasets (Table 1), it should be possible to develop statistical relationships between environmental characteristics and the prevalence of species targeted as relevant to industry biofouling concerns, for example mussels, kelp, and barnacles. Such statistical techniques and methodologies have been employed in previously published literature, suggesting that there is precedence for this work.

The outputs of the statistical studies mentioned above would be based on ‘natural’ species occurrence. Crucially, these statistical relationships must by validated in order to be relevant to fouling by targeted dominant species on marine infrastructure. The validation might be carried out using existing datasets obtained from marine renewable energy devices and other marine infrastructure around the UK (e.g. datasets from J. Loxton (ERI), A. Macleod (SAMS), and any existing industry data). The outcome of this validation will act as a decision point, determining the next steps needed to develop a biofouling map/tool. If successful prediction of biofouling characteristics (e.g. whether barnacle/kelp/mussel dominated) using relationships developed from existing ‘natural’ data occurs, it therefore suggests that sufficient biological data are available to move forward with developing a predictive map or tool.

If biofouling community composition cannot be predicted, other factors that have not been accounted for are likely to be also driving the observed faunal communities. These might include the structural considerations as discussed in Section 7.7. It may be that fouling communities on man-made structures are sufficiently different from those found in natural habitats that they cannot be predicted by the same environmental characteristics. While this would be a substantial finding in itself, it also further highlights the need for an industry-relevant protocol for recording biofouling and an associated central database. As the industry protocol develops and data availability improves, the information from such a database could be used to iteratively improve and/or redevelop statistical models to predict biofouling characteristics, which could then in turn be made available to database contributors and users.

It is worth noting that even with the best available environmental and biological data, there is a possibility that statistically significant relationships may not emerge. This is an important consideration, as confidence in these statistical relationships must be sufficiently high that they are robust for industry decision making, where financial investment and resource are important concerns. There may also be legal implications associated with providing advice to industry groups, so scientific outcomes must be robust. If no statistically significant relationships can be identified, it may be that the variability in biofouling community structure is such that it cannot be predicted by geographically linked environmental parameters, or that the predictive power of the model is better in some geographical locations than others. In the former case it is unlikely to be appropriate to develop a predictive map further, while in the latter case, the development of region-specific maps could be explored.

5.4 Mapping marine growth

Once developed through the iterative process, statistical relationships between environmental parameters and fouling community composition must then be mapped to UK waters, whether through a physical geographical map (Figure 9), or in relation to particular conditions characterising a suite of sites and general development types. A visual map would need to account for the three dimensional nature of the marine environment, which poses some challenges in data visualisation. Individual maps for particular depth zones could be created to resolve this problem, or for a particular location output information could include various scenarios for depths throughout the water column. Alternatively, starting with a simple geographical map, users might click on a location of interest and identify a depth of interest; from this information the relevant characteristics of marine growth is returned.

4. Figure 9: Examples of mapping formats with relevant datasets. Left: offshore renewable energy leasing sites, oil and gas production sites, and leased aquaculture sites around Scotland (from Marine Scotland’s National Marine Plan Interactive). Right: patterns of tidal power overlain (tidal power data available at www.renewables-atlas.info) with MNCR subtidal biology sampling sites (publicly available at http://data.nbn.org.uk).)
5. Biofouling thickness and roughness were cited as the characteristics most likely to affect the efficiency of devices (Figure 2). Characteristics associated with weight were also cited by respondents. Taken together, ‘hard growth’ (comprised of mussels, barnacles, and polychaete worms) that is both rough and thick should be considered as of the greatest concern to project developers and engineers
6. There is uncertainty associated with specific device tolerances to marine growth, including the types and/or levels of fouling which could affect the device function.

With this in mind, the key engineering considerations associated with the development of marine growth on marine renewable energy devices are summarised below. These include biofouling mass, thickness, surface roughness, heat transfer properties, corrosion, and impacts on wet connectors.

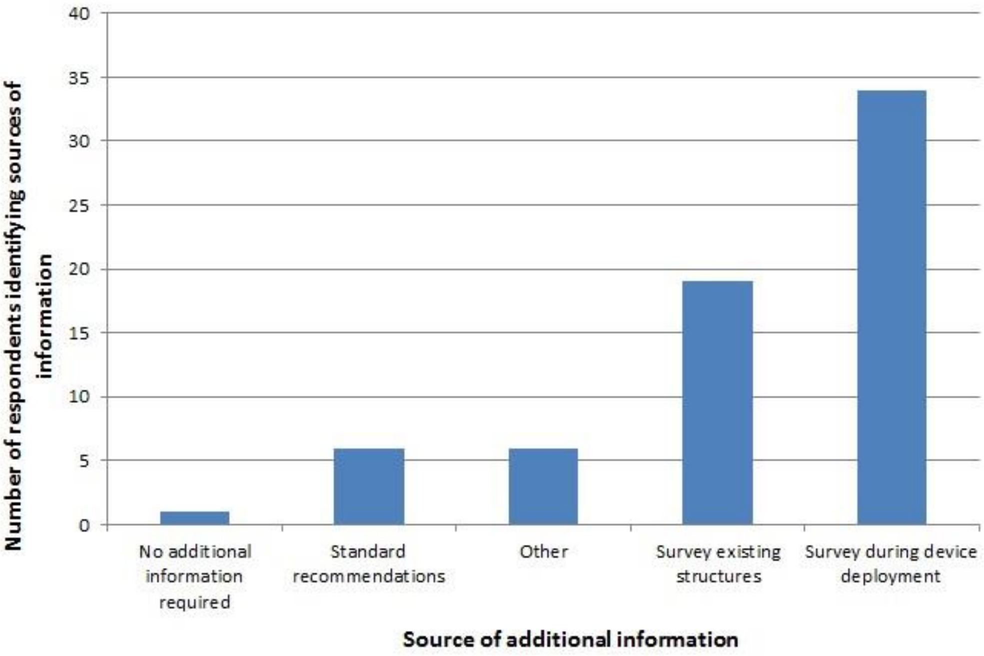

Figure 1: Sources of information and methods used by survey respondents to gather relevant data about biofouling characteristics associated with their device.

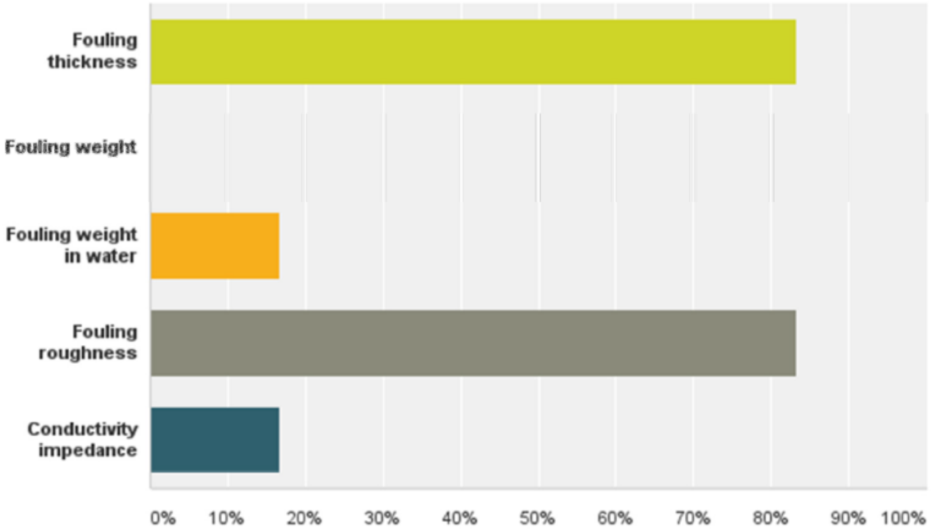

Figure 2: Biofouling characteristics cited by survey respondents as most likely to affect marine renewable energy device efficiency

5.5 Biofouling mass

5.5.1 Research

As part of a global analysis of biofouling pressure, the Global Approach by Modular Experiment (GAME) project analysed the quantity of biofouling biomass (wet weight) build-up on experimental settlement panels, discovering that rates of biofouling accrual were on average between 3g and 50g per week across the duration of the project (Canning-Clode & Wahl, 2010). In the temperate, exposed locations currently occupied by the majority of wave and tidal energy devices worldwide, the growth of biofouling is likely to be closer to the upper end of this spectrum as a result of greater flow rates, and high water column nutrient content, increasing the rate of added weight build-up on device components at these locations (Fox and Coe 1943; Langhamer et al., 2009). Biofouling samples taken from a network of navigation buoys throughout Scotland had sample wet-weights between 0.3 and 45.9 Kg/m^2 surface area (Macleod et al., *in press*). In Macleod et al. (*in press*), navigation buoys were selected from a range of geographical areas with different environmental conditions (tidal flow speed, temperature and salinity), and sampled after a range of deployment durations (1-6 years). The locations of the buoys were suitable for future potential development of renewable energy devices. Previous ecological studies have suggested that biofouling on foundations and mooring systems could be sufficiently substantial to affect the properties of the device (Witt et al., 2012). For wave energy devices located on the Irish west coast, simple population models suggested that marine growth had the potential to increase structural mass by over 10% of the total mass of the device (Tiron et al., 2012).

Outcomes of the industry survey, however, suggested that effect thresholds for biofouling mass on devices are unclear. Understanding the weight, weight in water and density of biofouling associated with biofouling mass was highlighted as key information needed to support engineering decision making, and is discussed further below.

5.5.2 Weight and weight in water

Marine biofouling can increase the weight of structures considerably, and in many situations can influence physical properties of the structure such as the buoyancy and susceptibility to fatigue. Biofouling weight is dependent on the volume of biofouling and the density of the material. These characteristics may be estimated by determining the species composition and the corresponding density, along with the thickness of the fouling and the geometry of the structure. Where the fouling community is dominated by a large volume of dense species (e.g. a mussel dominated community) the weight acting on the structure can be great. Conversely, where the density of species dominating the community is similar to the surrounding sea water (e.g. algae dominated community) the weight acting on the structure will be lower. To account for this buoyancy effect, biofouling mass can be calculated as weight in water in line with Archimedes' principle:

$$weight\ in\ water = estimated\ volume\ of\ fouling \times (estimated\ density\ of\ fouling - density\ of\ sea\ water)$$

5.5.3 Biofouling density

In situations where there is a lack of information regarding the biofouling weight, published recommendations can be used. For example, when determining the weight of fouling acting on a mooring line, DNV-GL recommends using a density of 1325kg/m^3 (Det Norske Veritas, 2013a). This will produce a conservative estimate and is based on the community being dominated by hard fouling species. However, where engineers require more precise estimates of weight (e.g. anticipating reductions in power conversion rates of wave energy devices through added inertia), more accurate predictions can be made by measuring the volume of hard fouling (those taxa with dense calcareous body parts) and soft fouling and assigning appropriate densities to them (1325kg/m^3 and 1050kg/m^3 respectively) (Mallat et al., 2014). In doing so, engineering tasks including mooring line fatigue analysis, power conversion assessment, and decommissioning assessments can be planned with greater precision. It is worth noting, however, that this technique may produce results substantially different from current industry standard guidelines, which have been cited as overestimating biofouling weight by up to 42% (Mallat et al., 2014). With this discrepancy in mind, it is important to develop and standardise improved techniques for measuring biofouling weight and to develop techniques for predicting biofouling weight from existing biological knowledge (Macleod et al., *in press*).

5.6 Biofouling thickness

Biofouling thickness was identified by industry representatives as an important characteristic of biofouling communities, and one where additional understanding and predictive abilities could support future decision-making. Structural drag and added mass coefficients are related to the effective diameter of the components in question (API RP 2A-WSD, 2000; Figure 3). Marine growth serves to increase the effective diameter of a structure (Figure 3), and can therefore alter the hydrodynamic forces acting on that structure. The estimated thickness under “operational” and “storm” conditions may change as the result of variation in the compressibility of different species (Marine Technology Directorate Limited, 1992). An understanding of biofouling thickness is also necessary in order to determine the volume of biofouling attached to a structure to estimate biofouling weight. Finally, the thickness of biofouling can influence other properties of submerged devices, such as their ability to dissipate heat across heat exchange surfaces (see Section 5.8: Heat transfer coefficient).

Both the type of species present and the rate of growth influence the resulting thickness of biofouling. Species composition and growth rates are in turn influenced by environmental characteristics including water depth, turbidity, geographical location, flow speeds, and duration of emersion. For example, studies have demonstrated that mussels will grow larger in areas of strong flow (Fox and Coe, 1943) or increased wave exposure (Langhamer et al., 2009), although in extreme, energetic areas organisms may be subject to regular disturbance from storm events and dislodged from structures. Even so, there is a degree of uncertainty associated with the thickness and growth rates of biofouling in the highly energetic marine environments associated with wave and tidal energy extraction, as few studies have been carried out at these locations.

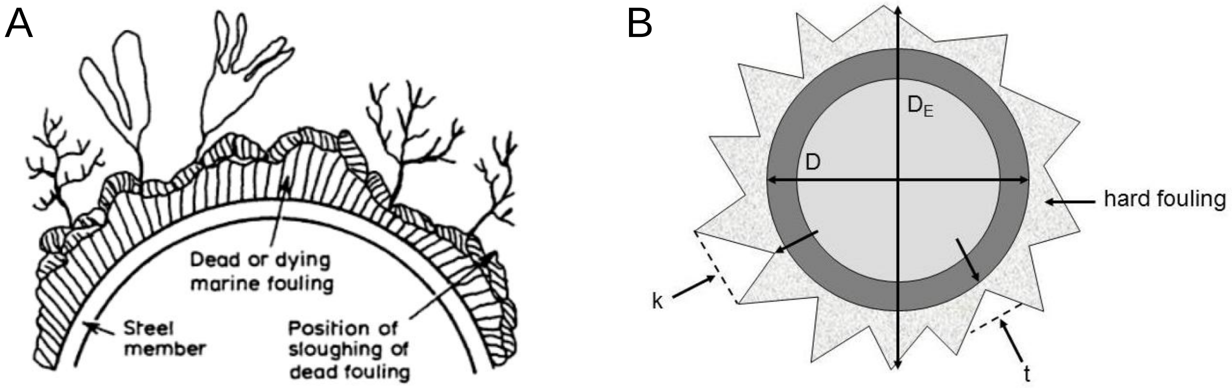

Figure 3: Modification of external structure due to biofouling. A) biofouling is composed of soft and hard structures. B) Changes in the effective diameter (DE), thickness (t) and roughness (k) of structural elements exposed to flow is increased as a result of biofouling. Adapted from Shi et al. (2012).

5.7 Surface roughness

Roughening of component surfaces was identified by survey respondents as a key characteristic of biofouling likely to affect the efficiency of wave and tidal energy devices, although in differing contexts for each technology type. Where fouling roughens moving parts, the potential for damaging abrasion and accelerated component wear increases. This was cited as a particular concern by wave energy developers, who highlighted the potential for damage to seals on pumping modules and to tethers. A tidal energy developer highlighted that substantial kelp fouling resulted in damage to otherwise effective antifouling coatings, as the motion of tidal currents caused kelp fronds to repeatedly rub against exposed device surfaces, abrading the coating and indirectly roughening the surface.

As a general rule, rougher structures tend to produce thicker boundary layers affecting loading criteria in different ways. Many standard methods exist to estimate the additional loading and these are dependent on the application and the characteristics of the surrounding flow (e.g. turbulence, periodicity) (Gudmestad and Moe, 1996); API Energy, 2005; Det Norske Veritas, 2013a. Surface roughness is typically a measure of the average height (k) making up the roughness elements (Figure 3b). The drag coefficient and added mass coefficient tend to be dependent on the roughness height relative to the diameter of the structural element (Theophantos and Wolfram, 1989; API Energy, 2005).

Perhaps of greatest concern noted by industry representatives developing tidal energy was the biofouling of turbine rotor blades negatively affecting blade hydrodynamics and the energy conversion rate. The majority of tidal turbines blades are designed to maximise lift forces generated by the blade geometry whilst minimising the drag force. Increased surface roughness and altered blade geometry reduces the efficiency of turbine blades decreasing overall power generation (Orme et al., 2001). As marine organisms begin to colonise the surface of a newly deployed device, the roughness of surfaces will generally increase. This process will depend greatly on the composition and size of colonising organisms. Although developers understand that small increases in biofouling on turbine blades could have substantial effects on blade performance, the relevant point at which biofouling begins to significantly affect turbine blade performance is unknown, with insufficient data currently existing to quantify this effect. Development of a microbial biofilm could be sufficient to produce a recognisable drop in blade performance, or, substantial barnacle or tube worm fouling may be necessary before significant effects on performance are observed.

Surface roughness height varies with biofouling species composition, but it is difficult to develop a reliable relationship between these two variables. The effect of soft flexible growth on drag coefficient is poorly understood. Some experimental data show that soft fuzzy growth (e.g. hydroids) has little effect on the resulting drag coefficient and that the underlying hard growth predominantly determines the drag coefficient (Nath, 1987). However, fouling by large flexible organisms such as kelps produces drag coefficients similar to those of hard growth (Nath, 1987). Variability in relative roughness height above 0.005 m has been shown to have a substantially lower influence on resulting drag coefficient than the presence/ absence of biofouling (API Energy, 2005). This suggests that the previously discussed issues of biofouling weight and biofouling thickness may be better candidates for attempting to use biological information in a predictive way to inform engineering decisions.

5.8 Heat transfer coefficients

Fouling at heat exchange surfaces is a complex challenge to address. The heat transfer coefficient is a key property of heat exchange surfaces, and is dependent on the difference in temperature between the solid surface and the surrounding fluid, and on the heat flux (i.e. rate of heat energy transfer through a given surface, per unit time) (Lienhard, 2008).

While microbial biofilms tend to have similar heat transfer coefficients to the surrounding fluid and do not appear to significantly impact heat exchange (Panchal, 1988), macrofouling, and hard macrofouling in particular, often have poor heat transfer properties. Furthermore, macrofouling may alter the shape of heat exchange components that have been designed to maximise surface area, further reducing heat transfer efficiency. Species specific effects on heat transfer and heat transfer coefficients are difficult to predict without intensive laboratory based research.

The effect of biofouling on heat exchangers was identified as an additional area of interest by developers of bottom mounted tidal energy converters. However, given the limited knowledge of how different biofouling communities affect heat transfer properties and the substantial research investment required to address this issue, it was decided to exclude it from further consideration.

5.9 Additional engineering considerations associated with biofouling

Further issues associated with marine growth on marine renewable energy devices identified from the industry consultation included corrosion, fouling of wet connectors, and interference with moving parts.

Biofouling can strongly influence corrosion rates by altering the chemical environment at the metal surface, and by causing mechanical damage to protective coatings. Furthermore, the combination of increased loading (see Sections 5.5 and 5.6) and corrosion enhancement as a result of marine growth can promote corrosion fatigue (Edyvean and Videla, 1991). Barnacles, for example, have been observed to compromise a range of protective coatings deployed in the UK's Pentland Firth; an area characterised by extreme water flows (Vance et al., 2014). Mechanical abrasion to coatings may also occur from contact between the structure and attached kelp macrofouling, providing opportunities for further fouling to attach, with implications for corrosion at those areas.

In the case of wet connectors, barnacle fouling was identified by surveyed industry representatives to obstruct successful coupling and de-coupling of connector elements. Surfaces at the connection interface are of particular concern, and the avoidance of exposure during seasons of high barnacle settlement rates could help to reduce this issue.

Finally, the detrimental impact of marine growth on moving mechanical parts was highlighted. Given the wide spectrum of device design, the impact of biofouling in this context will often be specific to the type and operational mode of the device. Even so, types of marine growth with negative effects on moving parts are likely to have several common attributes. For example, species which are non-compressible (with hard, calcareous body parts) and/or which attach strongly to the structure will have a greater impact on moving parts than soft, compressible species. This reinforces the need to predict where and when certain species groups such as barnacles and mussels are likely to represent a cause for concern.

5.10 Further questions to be addressed

The difference between 'soft' and 'hard' fouling has been highlighted as crucial to nearly every issue or concern associated with biofouling. Therefore understanding the environmental conditions and characteristics leading to development of 'hard' and 'soft' biofouling communities will be a critical element in the development of a predictive tool. The types of fouling communities can be broken down further with regards to certain common taxa of high relevance to the aforementioned topics: mussels, barnacles, and macroalgae. These taxa are often dominant within biofouling communities subjected to different conditions. Further discussion on particular biofouling taxa of interest, their ecology, and potential impacts on marine renewable energy devices can be found in Section 4 below.

6 Biofouling species of interest

6.1 Introduction

Once submerged, the component surfaces of marine structures become rapidly covered by a biofilm made up of bacteria, microalgae, and other microorganisms. This biofilm then enables the settlement and growth of a diversity of larger organisms, including ascidians (tunicates or sea squirts), soft corals, anemones, seaweeds (kelp), mussels, barnacles, and polychaete worms (tubeworms and others). The composition of these biofouling communities is shaped by the supply of larvae and propagules of these organisms and by a number of environmental characteristics. In the majority of cases, mature biofouling communities tend to be dominated by a few, highly abundant taxa. Biofouling communities that are composed of, and dominated by, similar species, are likely to have similar characteristics (e.g. roughness, weight).

As discussed in Section 3, biofouling thickness and roughness are characteristics most likely to affect the efficiency of devices. Furthermore, biofouling communities characterised by greater mass (i.e. dense hard growth) are also of concern. With this in mind, three key taxa that dominate biofouling communities which would have the greatest influence on these characteristics in relation to offshore renewable energy devices were identified:

- Mussels (blue mussel, *Mytilus edulis*)
- Barnacles (subtidal species, e.g. *Chirona hameri*)
- Large seaweeds or kelps (*Laminaria* spp., e.g. *Laminaria digitata*)

These taxa, illustrated in Figure 4, have been recognised as among the most common foulers worldwide by the GAME project (Canning-Clode and Wahl, 2010).

Mussels are a frequently dominant component of marine growth on man-made structures around UK coastlines, affecting both the surface roughness and weight of structures. Barnacles, too, are a commonly observed element of biofouling communities, and are commonly associated with increases in surface roughness and accelerated corrosion. *Chirona hameri* was chosen as a representative barnacle species as a result of its size, tolerance to flow and prevalence at the EMEC Fall of Warness tidal energy test site (Vance et al., 2014). Finally, kelp (specifically *Laminaria digitata*) was selected because of its notable prevalence on hard substrates characterised by higher flow rates and good light availability. Environmental surveys of marine renewable energy deployment sites have also noted the predominance of *Laminaria* spp. at some of these locations, suggesting that it could be a dominant contributor to fouling communities (e.g: Xodus 2010; Royal Haskoning, 2014).

Biofouling communities found in locations characterised by different environmental conditions (e.g. light availability, flow speed, depth) tend to be dominated by different species. Kelps are limited to near-surface components as they are dependent on light for photosynthesis, and do not flourish in turbid waters. Mussels, on the other hand, are highly successful in waters rich in particulate matter, particularly where flow rates are somewhat increased. This provides increased food supply to these filter-feeding organisms, allowing for greater mussel densities and growth rates. However, mussels do not tend to form dense aggregations on structures below approximately 30m depth, where barnacles can dominate (Forteath et al., 1982; Page and Hubbard, 1987). Even so, factors influencing the dominance of these two latter groups are complex, and can vary according to a variety of environmental and geographical factors (Cowie, 2010 and references therein). In the following sections the characteristics and life-history of each taxa is briefly discussed in turn.

Figure 4: Key dominant taxa in biofouling species assemblages. A) Kelp, *Laminaria digitata*, (Ardtoe - geograph.org.uk – 501243 David Baird), B) Barnacle *Chirona hameri*, (http://www.marinespecies.org/carms/, Claude Nozeres), C) Mussels *Mytilus edulis,* ("Cornish Mussels", Mark A. Wilson, https://en.wikipedia.org).

6.2 Kelp: *Laminaria* spp.

Three species of kelp dominate the intertidal and shallow subtidal zones around European coastlines: *Laminaria hyperborea*, *Laminaria digitata*, and *Saccharina latissima* (formerly *Laminaria saccharina*). Of these, *L. digitata* is most commonly found on offshore structures, being more adapted to energetic environments than *L. hyperborea* (Terry 1986; Tiron et al., 2012), and *Saccharina latissima* (Burrows, 2012).

Laminaria are large, conspicuous kelps commonly found growing on natural and man-made hard substrates. They are found around the majority of the UK coastline where suitable hard substrate is available, at depths between 1 m and 20 m. An individual kelp plant can grow to a length of 2 m to 4 m, with rapid growth occurring between the months of February and July. Growth rates of 1.3 cm per day have been reported during this season (Perez, 1971; cited in Kain, 1979). *Laminaria digitata* can grow in stands as dense as 40 kg/m^2 wet weight (Lewis, 1964), but as this species is close to neutrally buoyant, this weight is not exerted on a static host structure. Abrasion to structures may also occur as a result of contact between kelp fronds and the structure. Moreover, *Laminaria* presence could influence the hydrodynamic properties of the structure.

Laminaria digitata is found across much of the North East Atlantic, its range stretching from Russia in the north, to France in the South. While common around much of the UK's coastline, *L. digitata* is conspicuously absent from many areas on the east coast of England (Figure 5). Its distribution is limited by light levels, salinity, temperature, wave exposure, and desiccation (in intertidal areas).

Figure 5: UK distribution of *Laminaria digitata*. NBN Interactive map from http://www.marlin.ac.uk/species/detail/1386, accessed 04/12/15, map last updated 29/05/2008.

Kelp propagules are able to disperse at least 200 m from parental habitat, though dispersal distances in the order of kilometres are possible. This dispersal is driven largely by local currents (Norton, 1992).

6.3 Mussels: *Mytilus edulis.*

Blue mussels (*Mytilus edulis*) can be found on all parts of the UK coastline (Figure 6) and frequently dominate marine growth on offshore structures in the upper 30 m of the water column (; Southgate, 1985; Page, 2010). Globally, the predominant influence on *M. edulis* distribution is seawater temperature, but at the regional or local scale flow rates are thought to be an important determinant of mussel success (Seed, 1976). Mussels tend to do well and develop in dense aggregations where water flow is high enough to provide sufficient quantities of food, and to remove waste and inorganic material from the substrate (Seed, 1976). As flow rates increase, however, there is an increasing probability that mussels become detached from their substrate and transported elsewhere (Dare, 1976). Mussels have been observed to develop stronger byssal threads when attached to substrates subjected to high flows (Dolmer and Svane, 1994), but sudden storm surges or extreme flows may still be able to detach mussels from the surfaces they inhabit (Young, 1985).

Studies of oil platforms in the North and Celtic seas have observed *Mytilus edulis* to be the dominant component of biofouling on shallow submerged structures (Whomersley and Picken, 2003; Southgate and Myers, 1985). In the North Sea, mussels make up a substantial component of wind turbine foundation fouling, occupying 80% - 100% of space on foundations and monopoles from the sea surface down to depths of 10 m (Lindeboom et al., 2011).

Mytilus edulis on man-made structures have been reported to reach nearly 0.1 m in length, and grow faster in the Celtic Sea than in the North Sea (Page and Hubbard, 1987). With calcareous shells and high population densities, these organisms can exert substantial weight on a submerged structure, in addition to increasing the size (effective diameter) and roughness of structural components. A study in Brofjorden, Sweden, observed that biofouling communities on marking buoys were dominated by *Mytilus edulis*, and that the total fouling biomass did not change significantly over the course of the three year study. The authors also noted that for point absorber wave devices installed at the nearby Lysekil Wave Park, biofouling at the observed levels was unlikely to have a significant effect dynamic behaviour of the buoy suggesting a similarly small effect could be observed on wave energy devices of a comparable size (Langhamer et al., 2009).

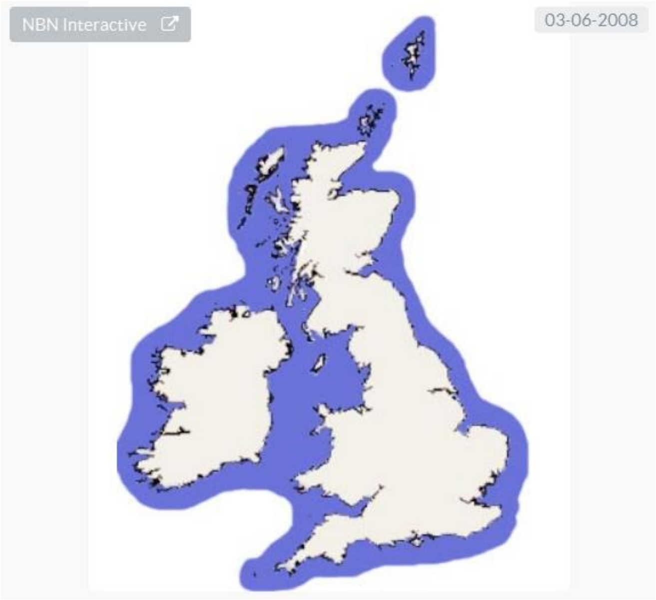

Figure 6: UK distribution of *Mytilus edulis*. NBN interactive map from http://www.marlin.ac.uk/species/detail/1421, accessed 04/12/2015. Map last updated 03/06/2008.

6.4 Barnacles: *Chirona hameri* and others

Barnacles can tolerate much higher current speeds and greater wave exposure than kelp and mussels, and so in many locations are more likely to be the dominant fouling species on marine renewable energy devices. While smaller subtidal species (e.g. *Balanus crenatus*) are common fouling species near the water-line and on shallow components of devices, the large deep-water species, *Chirona hameri* is often dominant at greater depths and in areas of extreme flows. *Chirona hameri* was the dominant species found on coating test panels deployed at the Fall of Warness test site (although other species of barnacle were also observed) (Vance et al., 2014).

Chirona hameri is found around all coasts of the British Isles and in the Arctic Ocean, North, and Celtic Seas (Southward, 2008). Adults are commonly found at depths of 20m to 200m, often growing on other biological structures such as horse mussel (*Modiolus modiolus*) reefs, or on man-made objects. *Chirona hameri* is highly gregarious, and forms clumps with offspring settling and growing on previously established adults. In areas of high flow, barnacle growth rates are not only faster, but individuals tend to grow larger (Crisp and Bourget, 1985). This is particularly evident from observations of large individuals in the Pentland Firth and on North Sea oil and gas risers reaching approximately 50mm basal diameter and 50 to 60mm in height. The largest recorded specimens have been 75mm in height (Southward, 2008), but anecdotal reports of even larger individuals are not uncommon.

As with mussels, latitudinal gradients in temperature are important for determining the global distribution of many barnacle species. At regional and local scales, however, food supply, currents and wave exposure levels have been demonstrated to be important determinants of barnacle distributions. For example, Burrows et al. (2010) observed that the size of the barnacle *Semibalanus balanoides* was greater in areas of high seawater chlorophyll a content (a proxy for food supply). In the same study, high population densities of barnacles were consistently associated with areas of high flow and wave exposure. Less information is available for *C. hameri*, but the unusually large specimens of this barnacle consistently found in the Pentland Firth (an area of high current flows) (Vance et al., 2014), suggests that this species is likely to follow a similar pattern.

Like *Mytilus edulis*, barnacles possess calcareous shells and can be considered part of the ‘hard’ fouling component, which contributes to structural mass, and increases in component size and roughness. More commonly found in deeper water, and increasing in size with flow rates, barnacles are of particular concern for fully submerged or bottom mounted tidal energy devices.

Mussel-, kelp- or barnacle-dominated communities are likely to be prevalent on different types of marine renewable energy devices at different locations, dependent on a number of physical and environmental parameters. As will be discussed in the forthcoming section, it may be possible to use these parameters in a location- and device- specific context to predict a potential generic biofouling community. However, using such data are dependent on identifying and refining existing data at a sufficient resolution, and the ability to develop, verify, test, and validate appropriate predictive algorithms.

7 Environmental predictors of marine growth makeup

7.1 Introduction

Biofouling species largely consist of organisms which possess two distinctive phases in their life cycles: a planktonic larval stage and a benthic (bottom-dwelling) adult stage (McQuaid, 2010). The development of biofouling communities, therefore, will be influenced by both pre-settlement processes, affecting larval stages, and post-settlement processes, affecting juveniles and adults after settlement on a surface (Fraschetti, 2002; Jonsson, 2004; Pineda et al., 2009).

Propagules (invertebrate larvae and eggs, and kelp sporophytes) are released into the water column by adults at source populations, and are transported with prevailing currents until a suitable site for settlement is reached, or until the propagule is no longer viable (Pineda et al., 2009). During this pre-settlement stage, at local and regional scales (on the order of 10’s m to 1km) the ability of propagules to arrive at and successfully settle on a structure will be the dominant influence on any biofouling community structure. At small scales (on the order of mm’s to m’s), chemical cues released by other organisms living on hard structures can also cause larvae to change swimming behaviour and to metamorphose to settled juveniles. The ability of individual propagules to settle on a substrate will also be influenced by fine scale turbulence and flows at mm to cm scales (Jonsson et al., 2004; Gaylord et al., 2002).

Post-settlement success is dependent on a number of water column properties, including temperature, salinity, and food availability, as well as physical characteristics including water velocities, wave exposure, and turbulence. Successful colonisation is also dependent on the competitive ability of a species under the prevailing environmental conditions, as well as its susceptibility to predation (Pineda et al., 2009).

Any number of these environmental processes could influence the characteristics of marine growth communities present on offshore renewable energy devices. In this section the focus is on those parameters which could feasibly be used for prediction at a UK-wide scale. The selected environmental predictors profiled below are physical parameters associated with data that are measurable and comparable across regions at sufficient resolution, for example, temperature, salinity, current velocity, and wave exposure. At metre to tens of kilometre scales, these parameters have been demonstrated to have significant influence on the composition of both natural and biofouling communities. Organism scale interactions (mm to m scale) are highly specific to particular locations and their associated substrates and species; thus such interactions are complex to predict at larger scales. These more local interactions include device scale turbulence, chemical larval settlement cues and predator interactions. Interactions at this scale could be profiled for each specific renewable energy device, but are less useful for the development of a generalised predictive tool.

As key taxa of interest with regards to marine renewable energy device biofouling, the remainder of this report focusses on parameters relevant to the distribution of macroalgae (kelps), barnacles, and mussels. Environmental parameters to be discussed include seawater temperature, salinity, food availability (e.g. nutrient or chlorophyll concentrations) current velocity, and wave exposure. The influence of device design in relation to environmental parameters is also discussed, for example the depth of submergence of device components, and whether a structure is floating or fixed to the seabed.

7.2 Seawater temperature

For many fouling species, seawater temperature is an important factor affecting global distributions. For example, *Mytilus edulis* is an arctic-boreal species which occurs from Svalbard in the north (78 °N) to the French-Spanish border in the south (43 °N), and is temperature limited outside of these geographic-boundaries. Fluctuations in ocean temperature transporting warm water northwards to Svalbard were cited as a main cause of the reappearance of *M. edulis* in that region (Berge et al., 2005). Similarly, the distribution of the kelp *Laminaria digitata* ranges from the southern coast of Brittany, France to northern Norway (Lüning, 1990), and thrives in water temperatures between 10 °C and 15 °C. Future projections of the large scale geographic distribution of this species predict a northwards retreat, as influenced by increases in seawater temperature (Raybaud et al., 2013). At global scales seawater temperature is also an important determinant of diversity in biofouling communities, with tropical regions hosting more diverse biofouling communities when compared to higher latitudes (Canning-Clode and Wahl, 2010).

At the limits of a species geographical range, seawater temperature can influence the reproductive rates, affecting the ability of the species to recruit to populations, thereby limiting abundances. This is particularly true for barnacles, including the common intertidal species, *Semibalanus balanoides* (Rognstad et al., 2014), though little information is available for the fouling species *Chirona hameri*.

At regional and local scales, however, variability in seawater temperature is likely to be a weaker influence on the makeup of fouling communities (Macleod et al., *in press*). For example, the growth of *M. edulis* on offshore oil and gas platforms situated off California, USA, was more closely associated with phytoplankton biomass (primary productivity) than seawater temperature (Page and Hubbard, 1987). Furthermore, within its range extent the prevalence of *Laminaria* spp. is more strongly related to local differences in current speeds and depth than to temperature (Kain, 1979).

While seawater temperatures are a substantial influence on the prevalence of particular biofouling species at global scales, it may not be as relevant to prediction of species assemblages around the UK coastline, except for those species with range limits within the British Isles (e.g. the barnacle *Semibalanus balanoides*). While seawater temperature will not initially be excluded from a predictive model of biofouling community characteristics, it could be less relevant than other physical parameters.

7.3 Seawater salinity

The UK coastline is punctuated by river outflows, estuaries, and sea lochs whose freshwater discharges can contribute to variations in coastal salinity levels at intermediate (m to km) scales. Many fouling species are highly tolerant to fluctuating salinity levels, making them common components of assemblages found in ports and harbours, and on vessels. The non-native barnacle, *Austrominius modestus*, is an excellent example of such a species, which has now become common on artificial structures in coastal estuaries in the UK?. The large fouling barnacle *Chirona hameri*, on the other hand, is not tolerant of fluctuating salinities, and so will rarely be found in nearshore environments in proximity to freshwater input (Davenport, 1976). While mussels are somewhat more salinity tolerant, the size and biomass of *Mytilus edulis* decreases with decreasing salinity levels (Westerbom et al., 2002). Other common fouling species may be less affected, such as the kelp *Laminaria digitata* which has been shown to be highly tolerant to fluctuating salinities (Karsten, 2007).

Salinity is likely to be a greater influence on biofouling communities for nearshore, coastal developments (e.g. Severn Estuary, wind developments in coastal embayments) than at offshore sites with substantial oceanic influence (e.g. West of the Hebrides, Irish West Coast). If included in a predictive model for biofouling community makeup, datasets will need to be of adequate resolution to reflect variability at appropriate scales to distinguish species preferences.

7.4 Food availability

Nutrient supply and light levels are generally inversely proportional, as light penetration into the water column depends on water turbidity. Turbid waters tend to be nutrient rich, and hence rich in food supply, but lower in light penetration. Meanwhile, those waters low in nutrients tend to have high light penetration and low turbidity. While turbidity may be related to high amounts of suspended sediment in the water column, it can also be related to elevated primary productivity (increased growth of photosynthetic plankton). The spring and summer phytoplankton blooms observed in satellite images are a good example of visibly increased water column turbidity resulting from increased primary productivity.

Dominant filter-feeder communities are often associated with enhanced nutrient supplies, particularly in areas of moderate to high flow (Burrows, 2012). It is likely that the dominance of mussels on fixed offshore platforms in the North Sea is related to increased flow rates in the vicinity of vertical structures hosting mussel-dominated communities, and higher nutrient levels. Wilhelmsson and Malm (2008) suggested that the dominance of *Mytilus* spp. on offshore wind turbine foundations in Sweden could be related to improved feeding and growth conditions provided by vertical monopiles, perhaps related to enhanced flow rates around the cylindrical structures (Abelson and Denny, 1997). This was also cited as a possible factor influencing the comparatively high barnacle biomass also observed at these sites.

Kelp and other macroalgae, on the other hand, tend to be more prevalent in areas of low chlorophyll concentrations and improved water column light penetration. In areas of high flow rates that typically characterise tidal energy sites, a shift from macroalgae to suspension feeders often occurs with increasing depth and decreasing light availability. At sites of high wave exposure and low chlorophyll concentrations, *Laminaria* spp. are often more prevalent (Burrows, 2012), which may be relevant for near-surface or surface-piercing wave energy devices.

Satellite observations of seasonal variation in chlorophyll concentrations and water turbidity (and/or light attenuation) are readily available (see Section 6) and could be incorporated into a predictive tool for assessing biofouling community development. This parameter could be particularly indicative for communities on near-surface or surface-piercing devices where the relative biomass of macroalgae and mussels might be dependent on water column light attenuation.

7.5 Current velocity

Water velocity can influence both pre- and post-settlement processes, which in turn affect the characteristics of marine growth on renewable energy devices. The strength and three dimensional structuring of current velocities in the vicinity of a device is dependent on tidal cycles, local bathymetry, weather conditions, and residual circulation patterns (Simpson and Sharples, 2012). Increases in velocity, turbulence, and shear stress have been shown to influence the likelihood of settlement in some common fouling species (e.g. hydroids, barnacles, bryozoans, molluscs, and polychaetes), both negatively and positively (Koehl, 2007 and references therein). Processes operating at a scale relevant to propagules such as fine scale turbulence, wakes, and surface shear will be important in determining attachment and settlement rates on specific components of renewable energy devices. However, these parameters would be better resolved for individual devices and components on a case-by-case basis, rather than as a part of a wider scale predictive map of biofouling. As a result, this report focuses on the larger scale relationships between current velocity and biofouling community patterns.

For a particular depth of water and location, the composition of marine growth has been demonstrated to change across a spectrum of flow conditions (Judge and Craig, 1997). In general, the extreme flows found at marine renewable energy sites may discourage species that are less adapted to high levels of hydrodynamic stress (Burrows, 2012). In higher flow environments, for example, the larvae of some species tend to ‘reject’ a surface and continue swimming more frequently than in lower flow environments (Koehl, 2007). Models of larval settlement have also suggested that the responses of larvae to differing flow environments could change settlement rates by up to an order of magnitude (Eckman et al., 1994), which could have substantial effects on the resulting community composition.

Near the surface and where turbidity is low, macroalgae may flourish, though the particular species composition may be related to flow speeds. Tiron et al. (2012) investigated the development of *Laminaria* spp. and other biofouling on wave energy converters in Irish coastal waters, noting that two species of *Laminaria* were possible biofoulers: *L. digitata* and *L. hyperborea*. *Laminaria hyperborea* is better adapted to lower light environments, and often out-competes other species of kelp in natural environments. However, *L. hyperborea* is susceptible to strong waves and currents (>3 m/s), while *L. digitata* can withstand higher current speeds and could be a dominant fouling species on near-surface structures in areas of strong current flows.

As light penetration decreases with depth, mussels often become dominant. Along natural coastlines, mussels are commonly observed down to depths of 5 m to 6 m. On offshore man-made structures, their depth range extends much deeper, potentially as a result of elevated flow rates increasing food supply at these locations (Abelson and Denny, 1997). As mussels are gregarious and grow upon one another, when underlying mussels die they may also detach other individuals from the substratum, particularly in highly tidal environments. This leaves other individuals more vulnerable to strong currents that could potentially dislodge them (Young, 1985). In locations of extreme flows, mussels may be unable to maintain attachment via byssal threads and may be replaced by more strongly attached, streamlined barnacles, such as *Chirona hameri*. The increased resistance of barnacles to tidal scour could explain the prevalence of large barnacles retrieved from high-flow locations such as the Fall of Warness, Orkney (Vance et al., 2014). Even so, it has also been suggested that in highly exposed sites colonisation of substrate by barnacles could facilitate the recruitment of mussels by providing crevices or small, sheltered areas for mussel spat to settle to (Seed and Suchanek, 1992).

Data on current velocities are widely available, resolved to a variety of scales. In the first instance, data from the UK Renewable Energy Atlas could guide prediction of the prevalence of some biofouling species, and is available at approximately one nautical mile resolution across the UK continental shelf (Figure 7).

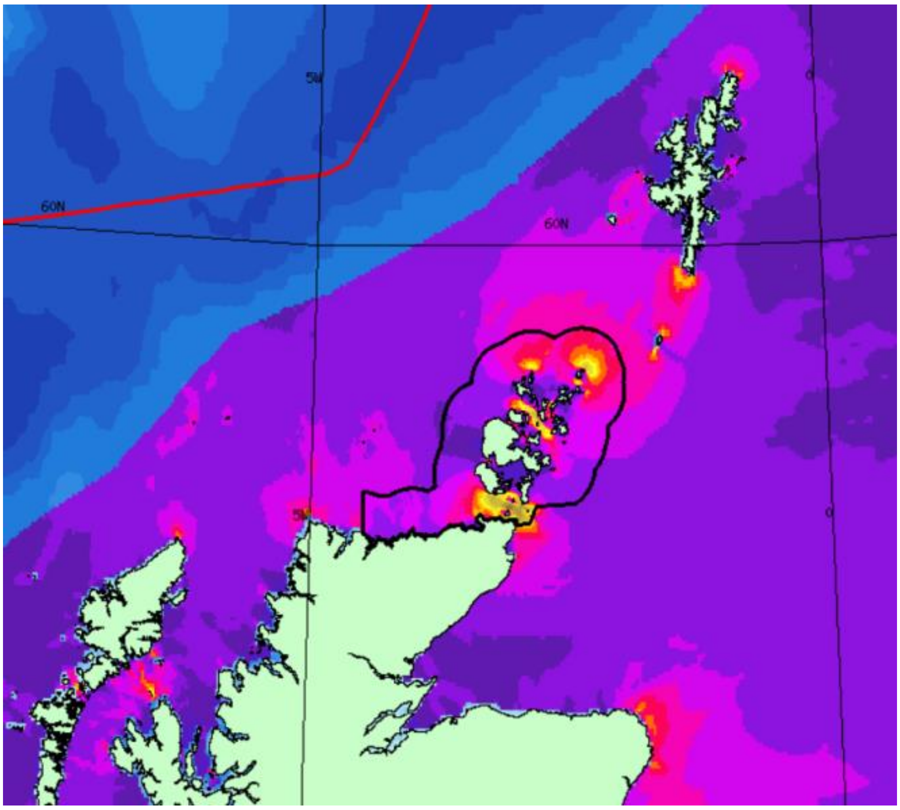

Figure 7: UK Marine Renewables Atlas Spring Peak Flow for the north of Scotland. Reproduced from http://www.renewables-atlas.info/,© Crown Copyright, accessed 04/12/2015.

7.6 Wave exposure

Wave exposure has been demonstrated to be an important predictor of intertidal and subtidal community structure on natural substrates (Menge et al., 1994; Burrows et al., 2010;Burrows, 2012). Previously, scientists have used the presence or absence of key species to provide an index of wave exposure in coastal environments (Ballantine, 1961). More recently, Burrows et al. (2009) developed and evaluated the ability of wave exposure indices to predict community structure at rocky shore sites across Scotland. Such indices were determined to have high predictive power, and so could be useful in predicting biofouling assemblages because of their ability to separate the influence of wave exposure from other factors. For example, exposed rocky shore sites were characterised by the kelps *Laminaria digitata* and *Alaria esculenta,* and the barnacle *Chthamalus stellatus*, species well adapted to high wave energy (Burrows et al., 2008). Similarly, kelps and barnacles could be reasonably expected to be prevalent species on surface-piercing offshore wave energy buoys in similar areas of high wave exposure. Few, if any, studies have directly profiled the effects of wave exposure as a predictor of deeper, subtidal communities. Wave energy also decreases with increasing water depth, which potentially limits its predictive power in relation to the characteristics of subtidal biological communities.

High wave energy may also result in more frequent disturbance to fouling communities by damaging or dislodging organisms, but it is unclear what effect this could have on biofouling on structures in extreme locations such as the west coast of the Outer Hebrides or the Irish west coast. Even so, variation in biomass on moored, floating structures such as wave buoys has been suggested to be more strongly related to exposure than to any other parameter (Langhamer et al., 2009). It is uncertain whether this effect extends to fixed structures, or to a particular depth of wave damping within the water column.

Data on wave energy or exposure are readily available. Quantified as mean annual wave height, wave exposure data are available from the Renewable Energy Atlas (http://www.renewables-atlas.info/), as generated from the Met Office UK Waters Wave Model; however, this dataset may not be of sufficient resolution for prediction of biofouling community characteristics (**Error! Reference source not found.**). Wave exposure indices generated from nowledge of wave fetch could be used to produce wave data at increased resolution, as demonstrated by Burrows et al. (2009), although such indices were generated from points along a coastline, rather than in coastal waters, and may need to be substantially adapted for offshore sites.

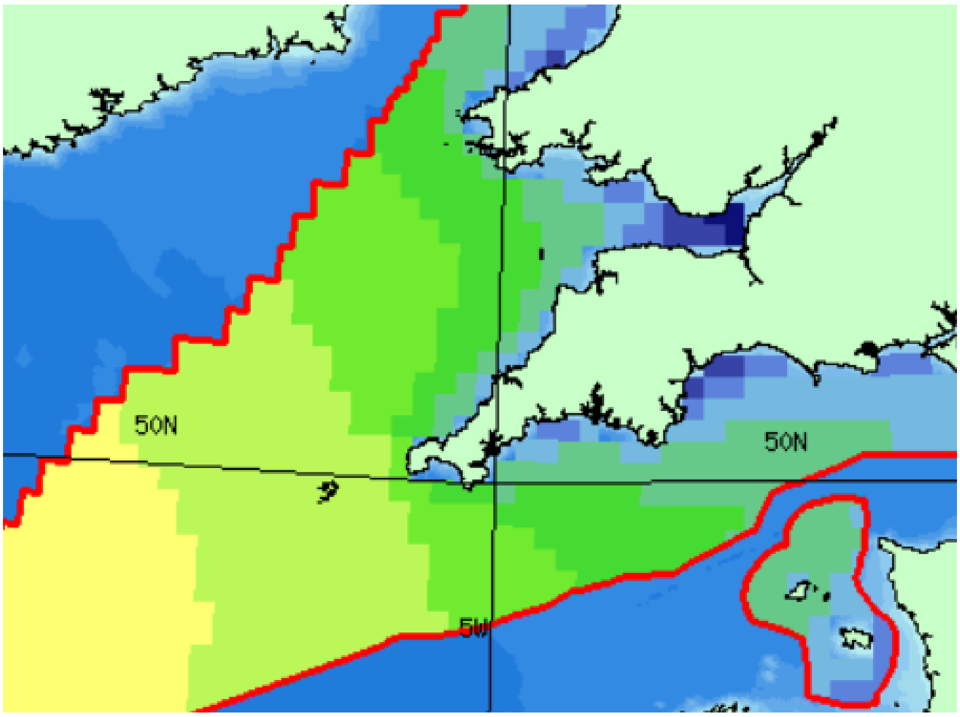

Figure 8: Annual wave heights calculated for Cornwall and southwest Wales. Reproduced from http://www.renewables-atlas.info/,© Crown Copyright, accessed 04/12/2015.

7.7 Structural considerations

While structural features unique to specific wave or tidal energy devices will not be discussed here, useful information can be gleaned by characterising devices as floating or fixed, surface-piercing or completely submerged, and in relation to the depth of particular structural features of concern. It is possible that such general information could be considered in the development of a mapping tool to predicting biofouling community characteristics and associated implications for structures.

In sheltered locations, experiment results have revealed substantial differences in the biological composition of biofouling communities between floating and fixed structures. These differences were attributed to the presence or absence of an intertidal zone, or a ‘swash’ zone, as well as to varying levels of exposure to light (Holloway and Connell, 2002). Similarly, floating renewable energy devices could be subject to different fouling communities than surface-piercing fixed structures (Miller et al., 2013). Completely submerged structures are likely to harbour biofouling communities in keeping with other environmental conditions at that depth. For example, for structures anchored or fixed within the photic zone where light can penetrate sufficiently for marine plant growth, kelp may be a substantial component of the biofouling community, up to certain flow speeds, beyond which, the community may be dominated by mussels. Deeper in the water column, barnacles might become dominant, as demonstrated in the ReDAPT project, where coated panels deployed at 42 m depth were dominated by the barnacle *Chirona hameri* (Vance et al., 2014).

Surface orientation, rugosity, deployment duration, and coating selection are all likely to influence the makeup of biofouling specific to particular devices. However, these may be secondary determinants of marine growth characteristics after the well-defined environmental and structural characteristics described in the previous sections. Once reliable predictions can be made based broadly on environmental and general structural features, individual developments and devices could then be subject to a subsequent, more detailed examination of potential biofouling based on device specific features such as small scale architecture, maintenance intervals, and coatings.

8 Environmental datasets for prediction of biofouling

8.1 Introduction

Numerous datasets are potentially available for use in the development of a predictive map of marine growth characteristics on offshore structures. It is worth noting that some characteristics such as temperature, seawater pH, salinity, and water velocity can also affect the performance of antifouling coatings (Chambers et al., 2006) particularly for biocidal coatings. Key guidance from the ReDAPT project suggests that it is prudent to characterise the marine environment in question in advance of specifying coatings for marine renewable energy devices and associated structures (Vance et al., 2014). As such, the datasets profiled in the tables below may also have use beyond marine growth mapping, in the field of coating specification.

There are challenges, however, in selecting appropriate datasets for development of a predictive model for marine growth. Understanding the spatial and temporal resolution required is important, as data are available across a wide variety of resolutions, and in the form of observational and interpolated information. Where possible, spatial data such as temperature and salinity should be resolved at the scale of a development, on the order of 1 km to 5 km, or 1/20º. Refining the resolution of parameters over to spatial scales relevant to fouling communities provides adequate information to distinguish between development sites. Higher resolutions for parameters such as wave exposure and current speeds, where available, should be used.

Many of the environmental parameters highlighted in the previous section are temporally variable, often varying with seasonal cycles and larger scale inter-annual phenomena such as the North Atlantic Oscillation (Hurrell et al., 2003). In these cases, decisions must be made with regards to the temporal resolution of data used. For example, sea surface temperature datasets are available in various formats, from seasonal mean values, to annual averaged values, to longer-term averaged values. Minima and maxima at each of these temporal scales could also be used. *Laminaria digitata* distribution, for example, seems to be most strongly related to annual maximum sea surface temperature, rather than annual means or minima (Raybaud et al., 2013).

With this in mind, a selection of commonly accessed oceanographic, environmental, and biological datasets and data sources are described in Table 1.

Table 1: Available environmental and biological datasets of relevance to predicting marine growth

Data type	Dataset name	Description	Availability	Resolution
Various	ICES	ICES (International Council for Exploration of the Sea) hosts one of the largest repositories for observational marine datasets worldwide. Relevant datasets include CTD data and temperature/salinity measurements.	http://www.ices.dk/marine-data/dataset-collections/Pages/default.aspx	Varies, depending on number of observations available at a particular location.
Various	BODC	BODC (British Oceanographic Data Centre) hosts publicly accessible observational marine data. Relevant datasets include CTD data, temperature/salinity measurements, and wave data series.	www.bodc.ac.uk	Varies, depending on number of observations available at a particular location.
Various	MEDIN	MEDIN (Marine Environmental Data & Information Network) hosts UK-focussed marine datasets gathered by both public and private organisations. Relevant datasets include wave data series, currents, bathymetry, and observational oceanographic data.	Data availability varies by dataset. Publicly available datasets available for download at www.oceannet.org. Accessibility information and relevant contact details provided for other datasets.	Varies, depending on number of observations available at a particular location.
Temperature	HadISST	Met Office Hadley Centre Sea Ice and Sea Surface Temperature data set	http://www.metoffice.gov.uk/hadobs/hadisst/ in plain text and NetCDF formats	1° latitude, approx. 110 km, available globally
Temperature	OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis – daily analysis of current SST for global ocean.	http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html	1/20°, approx. 5 km
Temperature	ODYSSEA	Atlantic European North West Shelf Ocean – ODYSSEA Sea Surface Temperature Analysis – mean	Available from the COPERNICUS Marine Environment Monitoring Service, www.marine.copernicus.eu	1/20°, approx. 5 km

Data type	Dataset name	Description	Availability	Resolution
		sea surface temperature at 1/20° resolution, from satellite data. Updated daily.		
Seawater optical properties	NEODAAS	Ocean colour data provided by the NERC Earth Observation Data Acquisition and Analysis Service. Includes high resolution chl a estimation from MODIS data.	https://www.neodaas.ac.uk/	500 m
Seawater optical properties	MODIS	Data from images from the MODIS Aqua satellite profiling chlorophyll a concentrations in mg/m^3.	Available from the NASA Giovanni data portal as time-averaged, monthly values, at http: //disc.sci.gsfc.nasa.gov/giovanni/	9 km
Bathymetry	EMODnet	Digital Terrain Model bathymetry based on bathymetric surveys, composite data sets, and GEBCO 30" gridded data.	http://www.emodnet.eu/bathymetry	1/8 arc minute, approx. 200 m
Tidal power	UK Atlas of Marine Renewable Energy Resources	Values of depth-averaged tidal power and velocity for the UK, derived from a depth-stratified model based at NOC Liverpool.	www.renewables-atlas.info	1.8 km
Tides	DTU 10	The DTU National Space Institute offers a global ocean tide model developed from satellite altimetry measurements from the TOPEX/POSEIDON, Jason-1 and Jason-2 satellites.	http://www.space.dtu.dk/English/Research/Scientific_data_and_models/Global_Ocean_Tide_Model.aspx	0.125° × 0.125° grid cells, approx. 14 km

Data type	Dataset name	Description	Availability	Resolution
Wave energy	UK Atlas of Marine Renewable Energy Resources	Wave data generated from the Met Office UK Waters Wave Model, which covers the majority of the UK continental shelf. Includes archival results for hourly wave data for 7 years previous.	www.renewables-atlas.info	1/9° latitude ×1/6° longitude, approx. 12 km x 12 km
Wave data	ICOADS	The International Comprehensive Ocean-Atmosphere Data Set provides numerous types of marine data from the last three centuries provided as monthly summaries at a variety of resolutions.	http://icoads.noaa.gov	1° x 1° grid cells, approx. 110 km x 70 km for UK
Wave Fetch	Burrows 2012	Wave fetch data generated by M. Burrows at SAMS (Burrows, 2012), for the UK coastline.	On request from SAMS.	Up to 100m
Biology	NBN Gateway	The National Biodiversity Network hosts a large number of publicly available biological datasets, including the Marine National Conservation Review. Records of particular species and habitat can be downloaded individually. Datasets are available for most species, most commonly available as semi-quantitative recordings using the SACFOR abundance scale. For some species, data are available as ‘count’ data, or species presence/absence.	Available from the NBN Gateway at https://data.nbn.org	Dependant on number of observations available at a particular location.
Biology	SNH benthic species dataset 1993-2014	Species records from benthic surveys commissioned by SNH or partners where the outputs are under the custodianship of SNH. Additionally species records determined from SNH analysis of third party	Available from the NBN Gateway at https://data.nbn.org	Dependant on number of observations available at a particular location. Semi-

Data type	Dataset name	Description	Availability	Resolution
		commissioned benthic survey video footage are included. The dataset contains surveys which contributed to the Marine Nature Conservation Review (MNCR) programme, EU funded BioMar Life project, SNH Site Condition Monitoring including broad scale surveys in support of the Natura process, surveys to establish the impact of specific activities on marine habitats and species and surveys to support the Scottish Marine Protected Areas project.		quantitative data available in SACFOR abundance scale, otherwise as abundance or presence/absence
Biology	JNCC Marine Offshore Seabed Survey Data	Dataset containing information about offshore benthic species and habitats, and their location within the UK's marine area. Data collected from a variety of research vessels using a range of survey equipment including grabs, underwater video and still images, and benthic trawls. Post survey analysis has been conducted by various contractors to identify species and their abundances. Abundance is recorded as count, SACFORN, or presence/absence.	Available from the NBN Gateway at https://data.nbn.org	Dependant on number of observations available at a particular location. Semi-quantitative data available in SACFOR abundance scale, otherwise as abundance or presence/absence
Biology	ERI Biofouling species lists	The Environmental Research Institute holds lists of species found colonising settlement panels installed at renewable energy test centres across Europe.	Held at the Environmental Research Institute, UHI, and potentially available through the UHI MERIKA project –access will need to be negotiated.	Site-specific to renewable energy test centres.

Data type	Dataset name	Description	Availability	Resolution
Biology	SAMS National Lighthouse Board Buoy Fouling	SAMS holds species abundance data from a series of campaigns sampling biofouling on offshore navigation buoys in Scottish waters.	Available at SAMS	Scotland-wide, but site-specific to navigation buoy locations.
Biology	EMODnet	EMODnet aims to provide a single access point to European marine biodiversity data and products, including biomass, abundance, and gridded abundance. Species groups include macro-algae and invertebrate bottom fauna. However, No layers exist for *C. hameri* or *L. digitata*.	http://www.emodnet.eu/biology	Dependent on data availability.

9 The feasibility of predicting marine growth from environmental datasets

9.1 Introduction

Marine ecologists have demonstrated that the makeup of intertidal and subtidal communities on natural surfaces is in many cases broadly predictable based on key environmental characteristics such as wave exposure, sea surface temperature, and chlorophyll concentrations (Burrows et al., 2008; Burrows, 2012). Theoretically, it should be possible to develop similar relationships between certain types of biofouling communities and environmental characteristics in order to map marine growth around the UK, provided that adequate environmental and ecological datasets upon which to base such a model are available. Once such relationships are developed, they could then be applied to a spatial model within a GIS system.

9.2 Availability of relevant biological and environmental datasets

Numerous relevant environmental datasets are publicly available at adequate resolution (Table 1) for integration into this type of statistical mapping study. There is precedence for use of these environmental data, as has been previously demonstrated in several marine ecological studies (Burrows et al,. 2008; Hawkins et al., 2009; Burrows, 2012; Mieszkowska et al., 2013). The acquisition and use of appropriate biological data may be a more substantial challenge. In previous studies, the relationships developed for natural environments were based on robust ecological datasets. For example, the UK's intertidal rocky shores are well understood and have been well studied over the past century, and reliable biological distributions are available for most key species. Subtidal communities are historically less well studied, but the UK's Marine Nature Conservation Review (MNCR) project has produced a high quality dataset of subtidal species abundances at locations around the UK coastline using standardised measurement methodology. This has allowed for quantitative assessment of the relationships between species distributions and local and regional environmental characteristics (e.g. Burrows, 2012). As described in Section 7.7, however, structural differences between natural and artificial habitats mean that relationships developed for subtidal communities may not be applicable to marine growth on artificial structures such as marine renewable energy devices (Holloway and Connell, 2002).

At present, publicly available biological datasets characterising offshore renewable energy device biofouling communities are rare, and standardised quantitative species abundance data are even more so. Some quantitative evidence can be gleaned from studies of oil and gas platforms and offshore wind energy installations (e.g. Forteath et al., 1982; Langhamer et al., 2009; Mallat et al., 2014), but these structures are unlikely to be subjected to the same degree of environmental stress (wave energy and tidal currents) as marine renewable energy devices.

As projects develop and more devices are installed, and as discussions around device fouling become more common, anecdotal evidence describing biofouling community composition is beginning to emerge with growing industry experience. This could form the basis of preliminary semi-quantitative relationships. Within the academic community, researchers are working to quantitatively characterise biofouling communities on and in the vicinity of wave and tidal energy devices. For example, the Environmental Research Institute, University of the Highlands and Islands, in Thurso are working to deploy settlement panels at wave energy test centres across Europe, to characterise biofouling and potential invasive species at each location (Dr. Jennifer Loxton, *pers. comm*). A dataset also exists characterising the fouling communities of navigation buoys deployed in a range of flow environments (from high to low) around the west coast of Scotland (Macleod 2013b; Macleod et al. *in press*), while the ReDAPT project has provided specific insight into potential fouling at the EMEC Fall of Warness test site (Vance et al., 2014).

While these biological data can provide a loose guide for developing the necessary predictive relationships between environmental characteristics and biofouling species makeup, a wider set of survey data obtained using consistent methods and with wide geographical scope would substantially improve the predictive ability of such relationships. One feasible approach to this challenge is to develop a standardised industry methodology or protocol for recording biofouling on installed devices, which could sit within existing operational activities. Metrics must be easily identified by an operator, and might include items such as dominant fouling type (e.g. barnacles/mussels/kelp/other), depth, and thickness, assessed in a simple, but standard way. While this might allow developers to track and better understand their own biofouling issues, if compiled into a central database, such information would form an important resource for future biofouling mapping and development of associated guidance. Such information could be incorporated into a wider database for wave and tidal energy projects, similar to the SPARTA database for offshore wind energy projects (see https://www.sparta-offshore.com). The development of such a protocol for data collection and of a complementary anonymised database might be the first task of an initiative taking this mapping study forward from the feasibility stage.

A further approach to this challenge might include the deployment of settlement panels at planned offshore renewable energy leasing sites around the UK coastlines across all seasons and in a variety of energetic environments to validate industry data gathered via the protocol described above. While inherently resource intensive, such a study could be achieved as a partnership between Scottish, English, Welsh, and Irish institutions.

9.3 Developing statistical relationships from available datasets

Given that information on biofouling from the extreme environments occupied by marine renewable energy developments is limited, the development of a map should be approached in two or three stages. First, using the wealth of biological data from ‘natural’ habitats (e.g. rocky shores and rocky subtidal habitat) and appropriate environmental datasets (Table 1), it should be possible to develop statistical relationships between environmental characteristics and the prevalence of species targeted as relevant to industry biofouling concerns, for example mussels, kelp, and barnacles. Such statistical techniques and methodologies have been employed in previously published literature, suggesting that there is precedence for this work.

The outputs of the statistical studies mentioned above would be based on ‘natural’ species occurrence. Crucially, these statistical relationships must by validated in order to be relevant to fouling by targeted dominant species on marine infrastructure. The validation might be carried out using existing datasets obtained from marine renewable energy devices and other marine infrastructure around the UK (e.g. datasets from J. Loxton (ERI), A. Macleod (SAMS), and any existing industry data). The outcome of this validation will act as a decision point, determining the next steps needed to develop a biofouling map/tool. If successful prediction of biofouling characteristics (e.g. whether barnacle/kelp/mussel dominated) using relationships developed from existing ‘natural’ data occurs, it therefore suggests that sufficient biological data are available to move forward with developing a predictive map or tool.

If biofouling community composition cannot be predicted, other factors that have not been accounted for are likely to be also driving the observed faunal communities. These might include the structural considerations as discussed in Section 7.7. It may be that fouling communities on man-made structures are sufficiently different from those found in natural habitats that they cannot be predicted by the same environmental characteristics. While this would be a substantial finding in itself, it also further highlights the need for an industry-relevant protocol for recording biofouling and an associated central database. As the industry protocol develops and data availability improves, the information from such a database could be used to iteratively improve and/or redevelop statistical models to predict biofouling characteristics, which could then in turn be made available to database contributors and users.

It is worth noting that even with the best available environmental and biological data, there is a possibility that statistically significant relationships may not emerge. This is an important consideration, as confidence in these statistical relationships must be sufficiently high that they are robust for industry decision making, where financial investment and resource are important concerns. There may also be legal implications associated with providing advice to industry groups, so scientific outcomes must be robust. If no statistically significant relationships can be identified, it may be that the variability in biofouling community structure is such that it cannot be predicted by geographically linked environmental parameters, or that the predictive power of the model is better in some geographical locations than others. In the former case it is unlikely to be appropriate to develop a predictive map further, while in the latter case, the development of region-specific maps could be explored.

9.4 Mapping marine growth

Once developed through the iterative process, statistical relationships between environmental parameters and fouling community composition must then be mapped to UK waters, whether through a physical geographical map (Figure 9), or in relation to particular conditions characterising a suite of sites and general development types. A visual map would need to account for the three dimensional nature of the marine environment, which poses some challenges in data visualisation. Individual maps for particular depth zones could be created to resolve this problem, or for a particular location output information could include various scenarios for depths throughout the water column. Alternatively, starting with a simple geographical map, users might click on a location of interest and identify a depth of interest; from this information the relevant characteristics of marine growth is returned.

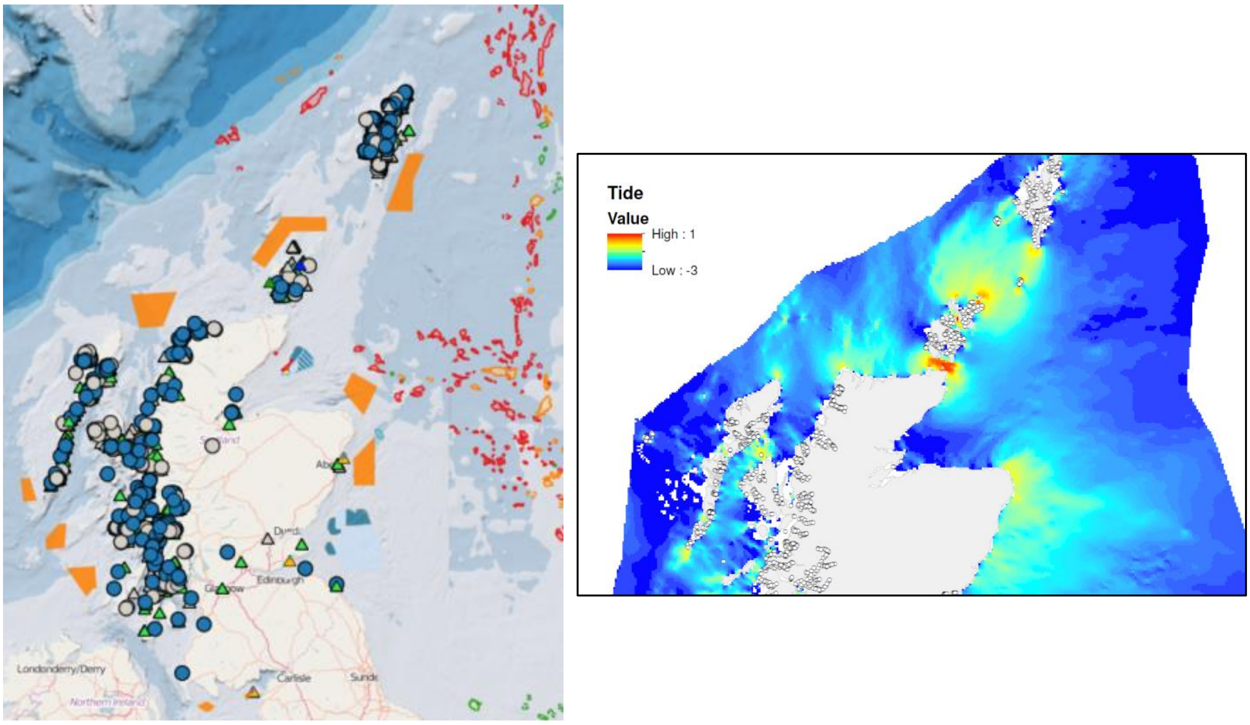

Figure 9: Examples of mapping formats with relevant datasets. Left: offshore renewable energy leasing sites, oil and gas production sites, and leased aquaculture sites around Scotland (from Marine Scotland’s National Marine Plan Interactive). Right: patterns of tidal power overlain (tidal power data available at www.renewables-atlas.info) with MNCR subtidal biology sampling sites (publicly available at http://data.nbn.org.uk).

9.5 Information output and interpretation

The information conveyed in a map or another predictive tool in relation to marine growth community makeup must be both relevant and easy to interpret by the desired users: renewable energy device engineers and site developers. For example, if fouling at a particular depth and location is predicted to be dominated by large barnacles, this could be translated as weight, surface roughness, and abrasion of moving parts on an installed device. Most barnacles release propagules in greatest concentrations in the spring, so in this example any device maintenance or cleaning might be most economical towards the end of summer, providing maximum time before new growth begins. Similarly, for a surface-piercing device in an area of high flow and low water column nutrient content, marine growth might be predicted to be dominated by large kelps, with implications for hydrodynamic drag and surface abrasion through contact with kelp fronds.

With further input from participants from the industry, outputs of a biofouling tool might also include parameters relevant for engineering purposes such as fouling weight, density (kg/m^3), and estimates of roughness. Associated growth rates for a particular dominant fouling species might also contribute to resultant characteristics, in light of potential implications for maintenance decisions. Finally, environmental conditions and predicted fouling makeup, when combined, could also be interpreted to guide antifouling paint and coating selection. In order to achieve these outcomes a programme of targeted industry consultation and communication of relevant science outputs will be necessary to ensure that a tool for marine growth mapping meets the needs of those who will use it most.

9.6 Summary of challenges

In order to develop a predictive tool for mapping marine growth and associated industry implications, three sequential project stages must be progressed, each with a key associated challenge (Table 2).

Table 2: Challenges of mapping marine growth in relation to stage of product development

Marine Growth Mapping Project Stage		**Key Challenge**
1)	Development and validation of robust relationships between environmental characteristics and biofouling community makeup (see 7.3)	Acquisition of relevant, quantitative biological datasets with sufficient power for multivariate statistical analysis (see 7.1 and 7.2). Successful validation of statistical relationships (see 7.3)
2)	Geographical representation of statistical relationships from stage 1 to enable location-specific estimation of likely marine growth (see 7.4)	Visualisation of three-dimensional datasets in two-dimensional space, either in map form, or alternative location-specific formats (e.g. regional guides to fouling, see 7.3)
3)	Interpretation and dissemination of mapped outputs in a format which provides relevant information to marine renewable energy device developers and engineers (see 7.5)	Identifying and understanding preferred metrics for biofouling quantification by end users, and accurate representation of metrics and other desirable information within the end product (see 7.4).

These challenges are by no means insurmountable, but will require additional investment of time and resource from marine scientists and engineers to overcome them. While the preferred solution might be to undertake a substantial, resource-intensive field campaign with a quantitative, standardised approach to characterising fouling communities at offshore renewable energy sites and on artificial substrates across a variety of environmental regimes, this is unlikely to be feasible in the current economic climate. Development of an industry protocol for collection and management of biofouling data in an anonymised fashion (Section 9.2) might be a cost-effective alternative. This initiative could be combined with existing datasets such as those held at the Scottish Association for Marine Science (Macleod, 2013b, Macleod et al., *in* *press*) and at the Environmental Research Institute (Jennifer Loxton, *pers. comm*) and supplemented with other existing biological data from offshore wind farm sites and/or oil and gas platforms. The resulting database could begin to provide a valuable picture of geographical variation in biofouling characteristics in relation to the physical environment of installation.

Challenges 2 and 3 will need to be addressed collaboratively between marine scientists and industry partners. To do so, it will be necessary to first develop a mutual understanding of the capabilities and needs of each party, through information sharing and knowledge exchange. For example, engineers may not be aware that ecologists are often able to predict the season of greatest settlement of biofouling organisms, making it difficult to understand how seasonal differences in deployment and maintenance practices could affect biofouling communities. Through further discussion, however, an index of biofouling growth rates and/or added weight might emerge as a more important metric for ecologists and engineers to focus on. This type of iterative, discursive process will not only help to address the specific challenge of optimising metrics for biofouling for both ecologists and industry representatives, but will also help to build a dialogue to address future issues in the field.

9.7 Opportunities for further development

The proposed map of marine growth or associated predictive tool will provide the marine renewable energy industry insight into the likely biofouling community types that could establish on their devices, and the resulting effects on the device. At its most simple, the product could provide an index of fouling type (hard/soft or barnacle/mussel/kelp), growth rates (high/low/intermediate), surface roughness, and/or added weight. While this project has been initially focused on the marine renewable energy industry, the nature and geographical scale of datasets feeding into the map mean that with further development, the predictive outputs from a map or tool could be useful across a broader range of industries (e.g. offshore wind and aquaculture).

The effectiveness of antifouling coatings is also influenced by the physio-chemical properties of the surrounding water. On a UK scale, seasonal variation in seawater temperature is greater than geographical variation: with water temperatures fluctuating seasonally across a similar range around Cornwall as around the north of Scotland. Variability in salinity, however, is greatest with respect to smaller scale geography, where the influence of river outflows, estuaries can have a more substantial impact on salinity levels. Mapping these two parameters together, and in combination with indices of predicted marine growth, it could be possible to provide improved location-specific guidance on paints and coatings.

Finally, as briefly discussed in Section 2, the occurrence of non-native species in UK waters is becoming an issue of greater concern for ecologists, industry developers, and regulatory bodies alike. With long-term development, it is possible that this type of map could provide additional information to offshore developers about the likelihood of species invasions at their sites in relation to site-specific characteristics, informing the development of biosecurity plans and measures to prevent the establishment and spread of invasive non-native species. Substantial development work would be needed, however, to ensure that such an addition is reliable and accurate, particularly when resulting outputs are incorporated into planning measures whose outcomes have legal implications.

10 Recommendations for future study

10.1 Barriers to mapping marine growth

Section 6.4 identified clear challenges involved in the development of a map of marine growth. Table 3 builds on those challenges and identifies potential barriers to taking forward a project to map marine growth, as well as measures that could be taken to mitigate them.

Table 3: Potential barriers associated with developing a biofouling map or product to predict biofouling implications for offshore renewable energy devices, with potential strategies for mitigation

Barrier	**Mitigation**
Insufficient ecological data resolution for biofouling communities to develop robust statistical relationships with environmental characteristics	1) Develop an industry-relevant system of recording, storing, and managing biofouling data for industry and academic use, increasing data availability, as discussed in 6.1. 2) Develop relationships using wider datasets from other offshore structures (e.g. wind) in addition to existing marine renewable energy-specific ecological data. 3) Simplify relationships developed, moving from abundance to presence/absence of species, or from species to fouling characteristics (e.g. rough, smooth, and heavy). This is least preferable.
Relationships between biological and ecological datasets do not emerge	1) Thorough review and quality check of input environmental parameters to ensure these are the most appropriate for prediction. 2) Take advice from expert biogeographers and marine ecologists with regards to statistical approaches.
Emerging environmental – ecological relationships are not relevant to the marine renewable energy industry	1) Industry stakeholders will be engaged in order to develop mechanisms for optimising interpretation of ecological biofouling information to relevant engineering outcomes.
Legal barriers may exist to providing guidance or advice to industry groups, particularly if used as a basis for operational decisions.	1) Consult with the Offshore Renewable Energy Catapult and funding bodies on previous experience with this type of initiative and seek advice from organisational legal teams.

10.2 Suggested approach and work plan

The development of a predictive map for biofouling should be undertaken following these three complementary work streams in the first project stage:

1. Development of industry-specific protocols for collecting information about biofouling, to be stored and managed in an anonymised database (see 9.2), to contribute to development of further guidance and mapping initiative.
2. Development of improved relationships between dominant biofouling communities and characteristics such as weight and surface roughness, specific to the wave and tidal energy industries, to be incorporated into further guidance and mapping initiatives.
3. Development of statistical relationships between environmental parameters and the prevalence of biofouling species of interest to renewable energy developers, using the 3-step approach described in 9.3.

Each of these work streams would then feed into the second stage, the development and maintenance of a biofouling mapping tool, provided that it is deemed appropriate to continue at each stage-gate within the process (for example as described in 9.3).

The knowledge exchange element of this project will be essential. It will be imperative to the project that marine scientists have a thorough understanding of the engineering challenges faced by renewable energy device developers and engineers, so that they can target the most relevant biological outcomes across all elements of the proposed project / stages. Likewise, developers and engineers can glean vital information from researchers at all stages of this project, to influence their own project outcomes across the project duration. Effective knowledge exchange will encourage innovation within the project, assuring successful outcomes for all parties involved, as well as good value for money in terms of impact for funding bodies.

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