CATAPULT
Offshore Renewable Energy

Marine Growth Mapping and Monitoring

Feasibility of Sensor Development for Monitoring Marine Growth

March 2016

PROJECT PARTNERS:

NERC SCIENCE OF THE ENVIRONMENT

PML | Applications Ltd

Document History

Field	Detail
Report Title	Marine Growth Mapping & Monitoring
Report Sub-Title	Feasibility of Sensor Development for Monitoring Marine Growth
Client/Funding	Part public funding by NERC
Status	Public
Project Reference	PN000111
Document Reference	PN000111-SRT-002

Author Revision Status

Revision	Date	Prepared by	Checked by	Approved by	Revision History
1	17.12.15	Anna Yunnie (PML Applications)	Tom Vance (PML Applications)	Tim Fileman (PML Applications)	Reviewed by Vicky Coy (ORE Catapult) 7.01.16
2	15.1.16	Anna Yunnie (PML Applications) Tom Vance (PML Applications) Richard Ramsden (AkzoNobel)	Tom Vance (PML Applications)	Tim Fileman (PML Applications)	Reviewed by Vicky Coy (ORE Catapult) 03.02.16
3	08.02.16	Anna Yunnie (PML Applications)	Tom Vance (PML Applications)		

ORE Catapult Revision Status

Revision	Date	Reviewed by	Checked by	Approved by	Revision History
1.0	04/03/2016	V. Coy	S. Cheeseman	P. MacDonald	Final Issue

Disclaimer

Contents

List of Figures

List of Tables

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 third element of this project, sensor development for monitoring marine growth.

Firstly, the potential benefits of developing a biofouling sensor technology for the renewable energy industry are examined. Secondly, the technical requirements of such a biofouling sensor are identified. Thirdly, a review of existing biofouling technology is presented and the gaps between what is currently available and what the renewable energy industry would require are discussed. Lastly, suggestions are made about the feasibility of conducting a biofouling sensor development project and what such a project might consist of in terms of work flow, time scales and project partner attributes.

This review concluded that if the concept of a biofouling sensor development project is considered with the renewable energy as the sole target market, the project looks unfeasible. However, if a biofouling sensor technology was developed that was capable of serving the renewable energy industry and also capable of providing the same cost savings to other larger and more developed marine industries such as shipping and Oil and Gas, in the short-term, the

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

project appears feasible. This scenario would allow the renewable industry to benefit from such a technology when the market requirement was present.

It also became clear that no single existing technology meets the requirements of an offshore renewable energy device biofouling sensor. In addition, it seems likely that any technology developed for microfouling would not be suitable to monitor macrofouling, and vice versa.

In conclusion, if a sensor technology, or technologies, were developed that were capable of serving the renewable energy industry as well as other more established marine industries, and incorporated a flexible element into the design to allow additional functionality to be retrofitted, we suggest the project is feasible, potentially lucrative, and beneficial to the environment and to the wider marine industry.

1 Introduction

Offshore tidal and wave renewable energy devices are an emerging technology. Consequently, efforts are focused on the overall design of such devices to maximise energy extraction potential and minimise costs. However, more established marine industries have already witnessed the impacts of marine biofouling organisms due to increased drag, increased weight and resistance on submerged structures. More information on the general physical effects of marine biofouling in relation to the renewable energy industry can be found in Feasibility of Predictive Mapping of Marine Growth, ORE Catapult, (2016).

An industry consultation undertaken for this project revealed that the negative effects of marine biofouling have already been experienced by some device developers during full scale prototype device testing. However, the true potential of biofouling to increase the cost of marine renewable energy generation is likely to be recognised as the industry develops and more infrastructure is deployed and requires asset maintenance.

Based on our experience of working with the marine renewable industry, and a wide range of other marine industries, we consider that in order for the marine renewable energy industry to overcome the potential challenges associated with biofouling, several key aspects are required. These include:

1. General realisation within the industry of the potential for biofouling to cause negative operational issues to offshore renewable energy devices.
2. Understanding of the risk to specific components or processes on offshore renewable energy devices to impacts from biofouling.
3. Characterisation of the spatial and temporal scales of biofouling occurring in current and proposed offshore renewable energy device sites.
4. Characterisation of the physical characteristics of biofouling on spatial and temporal scales.
5. Optimising offshore renewable energy device design to minimise the initial occurrence of biofouling and aid on-going inspection and maintenance.
6. Selecting optimum biofouling control technology and maintenance techniques.

Many of these aspects, especially 1, 3 and 6, could be addressed by the proposed biofouling characterisation mapping work (Feasibility of Predictive Mapping of Marine Growth, ORE Catapult, 2016).

The other aspects, especially 2, 5 and 6, could be addressed by the development of a biofouling sensor technology.

The development of a sensor to measure biofouling accumulation in real time would offer operators several advantages. Real time monitoring would inform biofouling removal operations so that removal is undertaken with optimal timing to provide the longest possible window between maintenance events. It would allow developers to differentiate between reduced energy conversion resulting from biofouling related drag and mechanical failure. It could also be used as part of a Biosecurity Plan to demonstrate awareness and monitoring of non-native species (NNS) that will help avoid unnecessary spread and potential prosecutions. Further potential to the industry and the feasibly of developing such a technology are presented in the following sections.

Firstly, in order to present a fully comprehensive review, the potential benefits of developing a biofouling sensor technology for the renewable energy industry are examined. Secondly, the technical requirements of such a biofouling sensor are identified. Thirdly, a review of existing biofouling technology is presented and the gaps between what is currently available and what the renewable energy industry would require are discussed. Lastly, suggestions are made about the feasibility of conducting a biofouling sensor development project and what such a project might consist of in terms of work flow, time scales and project partner attributes

2 Potential Benefits of Biofouling Sensing Technology

2.1 Reducing maintenance costs and health and safety risks

2.1.1 Situation

Regardless of antifouling measures, most structures exposed to seawater will eventually become fouled and require maintenance. Based on industry consultation activities conducted as part of this study, the majority of device developers and operators suggested that their decision to take action to remove or manage biofouling would be informed by visual inspections of their devices. Currently, inspection of an offshore renewable energy device requires direct access to the structure in-situ, which presents several problems.

The depth of water and distance from shore of typical offshore renewable energy devices prevent regular access to subsurface areas and components. These factors restrict the ability to perform regular inspections to determine the integrity of structures and coatings, and to manage biofouling. In the case of tidal turbines, the ability to gain access to the device can be further hampered by strong tidal streams, frequently accompanied by short and unpredictable slack water periods.

Access to most tidal offshore renewable energy devices is achieved through carefully planned missions with vessels equipped with Dynamic Positioning Systems (DPS) and/or Remote Operated Vehicles (ROVs). For specific jobs that require dexterity or access not achievable using ROV technology, commercial divers are deployed. All of these approaches are costly, especially the charter of DPS vessels. The cost of conducting these operations to perform maintenance or inspections is further escalated by the requirement to plan for downtime during inclement weather which can affect marine energy generation sites.

In addition to the cost element, the inherent health and safety considerations of commercial diving also adds risk to marine operations. This is a particular concern for the fledgling renewable energy industry that is striving to perform better than other established marine industries (such as Oil and Gas) in order to meet modern health and safety standards to secure investment.

2.1.2 Benefit 1

A suitable biofouling sensing technology would serve to reduce both the cost and health and safety implications of conducting maintenance. This would be achieved by providing a real time data stream that would inform operators of the optimum time to conduct maintenance based on real biofouling levels, rather than expected or predicted levels. This would allow operators to take advantage of seasonal and spatial variation in biofouling levels and only conduct maintenance when absolutely necessary to ensure the longest possible service intervals, reducing the costs and safety issues associated with biofouling maintenance.

2.2 Sensor and instrument maintenance

2.2.1 Situation

Most offshore renewable energy devices are heavily instrumented with devices such as Acoustic Doppler Current Profilers (ADCPs) or Acoustic Doppler Velocimeters (ADVs); similar technologies for measuring tidal velocities or turbulence. These instruments perform a vital role in helping to assess the performance of a single offshore renewable energy device, providing feedback to inform the optimum settings for a particular device to maximise energy conversion, and also determine cumulative effects of multiple devices.

However, these instruments are frequently colonised by biofouling organisms which can interfere with the instrument's data capture process. This is particularly the case for hard calcareous species which can interrupt the transmission of acoustic signals. One typical example of such an organism is the large barnacle *Chirona hameri* which is prevalent in tidal streams such as The Fall of Warness, Orkney.

When biofouling occurs on instruments involved in the operation of offshore renewable energy devices, it is not always clear whether unusual data patterns occurred as a result of signal degradation from biofouling or genuine hydrodynamic conditions.

Figure 1: Image showing macrofouling on an ADCP after 8 months in Orkney

This aspect is traditionally overlooked in typical oceanographic uses of ADCPs and similar instruments where deployments are generally limited in duration by battery life to one or two months. During such short deployments, the effects of biofouling can usually be overcome. However, the renewable energy industry is likely to use ADCPs and similar instruments for much longer deployments in areas where biofouling can occur rapidly.

2.2.2 Benefit 2

A fit-for-purpose biofouling sensor would be able to alleviate this issue by measuring biofouling in the proximity of a particular instrument and informing the operator when biofouling of a critical threshold occurs. This would allow the operator either schedule maintenance in sufficient time to ensure a genuine data stream, or be clear about when data quality from the instrument is compromised

2.3 Structural surveys

2.3.1 Situation

In order to ensure the structural integrity of underwater steel structures for Type Approval or insurance purposes, it is a requirement to undertake regular surveys to determine the thickness of metal and examine welds, detect cracks and measure corrosion rates.

In other marine industries, thickness measurements for example are frequently obtained by divers or ROVs using ultrasonic echo gauges. Most measures of structural integrity such as thickness or visual inspection of welds require the area being inspected to be free from fouling. This presents a problem for the marine renewable industry which operates in relatively shallow and productive waters where biofouling may interfere with accurate structural surveys.

In order to undertake survey work, it is likely that management or removal of biofouling would be required before the survey can be conducted. This pre-survey maintenance is likely to involve the contracting of specialist ROV or diving operators at a considerable cost and has potential health and safety implications especially when the survey requirements of large array of devices are considered.

2.3.2 Benefit 3

A real-time biofouling sensor technology has the potential to reduce costs and improve efficiencies associated with routine structural integrity surveys by providing a data stream to describe the level and type of biofouling at critical survey points on the device. This will allow:

- device operators to understand how much biofouling removal is required prior to survey work and thus inform likely asset management costs and maintenance timescales.
- the option of conducting biofouling management during other routine operations at regular intervals to reduce the time required from high cost, specialist contractors.

2.4 Non-native species

2.4.1 Situation

Non-native species, and specifically invasive species (a term used to denote species that have a detrimental effect when introduced to a new environment) have become the subject of incoming legislation, both in the UK and the EU. This may affect offshore renewable energy devices.

The ‘EU Biodiversity Strategy to 2020’ Target 5, titled ‘Combat Invasive Alien Species’, states that by 2020 invasive alien species (IAS) and their pathways will be identified, and of specific relevance to any mobile anthropogenic marine structure- pathways will be “managed to prevent the introduction and establishment of new IAS”. It is possible that man-made structures will be viewed as potential pathways and therefore likely to be a priority substrate type in the marine environment legislation.

Emerging legislation, which is already in effect in Scotland and anticipated to follow in the rest of the UK, states that it is an offence to cause any animal or plant to be at a place outside its’ native range (Wildlife and Natural Environment (Scotland) Act 2011). Failure to comply can lead to costly charges for eradication and environmental restoration. However, the legislation also states that where it can be shown that all reasonable steps have been taken and due diligence has been exercised to avoid committing an offence, an offence would not have been committed.

The opportunistic nature and propensity of settlement on anthropogenic substrates by NNS renders offshore renewable energy devices vulnerable to such settlement, and therefore owners need to be vigilant and take all precautions to prevent potential litigious situations when moving or cleaning devices.

NNS of noted concern, either environmentally or economically, generally fall into the macrofouling category by nature of their conspicuousness. It can be confidently assumed that any macrofouling assemblage will contain a number of NNS; however it should be noted that not all are necessarily deemed detrimental to the environment, health or the economy.

A judicious approach would be to monitor fouling type, as well as levels, during routine management observations. While it is not envisaged that most fouling sensors would be able to determine the identity of any given fouling organism, the ability to differentiate between microfouling and macrofouling would be highly advantageous in forming management plans.

2.4.2 Benefit 4

In order to demonstrate that reasonable efforts have been taken to ascertain the risk of a particular device harbouring NNS, it would be a requirement to monitor biofouling across the entire device. This could be partially achieved through time consuming and expensive ROV surveys. Alternatively, this monitoring could be provided by a biofouling sensor technology that could differentiate between microfouling and macrofouling, and therefore predict the risk of species of concern occurring on a device.

In this capacity, a sensor, or sensors, that monitored components at high risk of fouling would simultaneously inform management decisions for cleaning regimes on important working parts, and provide an indication of risk that the device was supporting NNS. This would clearly be evidence of ‘exercising due diligence’ and taking ‘reasonable steps’ against the transportation and subsequent introduction of NNS.

2.5 Trouble shooting

2.5.1 Situation

As previously described, most offshore renewable energy devices are highly instrumented and provide data streams back to their operators describing the performance of the device in terms of energy conversion rates or the status of critical components. This ensures the device is kept operating as efficiently as possible in between costly and time consuming deployment and retrievals.

Long-term decreases in overall device efficiency or the effectiveness of a particular component or system may occur. This could be as a result of wear and tear of components, or damage from the operational environment. This potential loss of performance can be monitored and action can be taken if efficiency drops below a critical threshold which can differ between systems and components.

As it is not technically practical to monitor every component within an offshore renewable energy device, the condition of systems and components are frequently assumed based on proxy measurements such as overall device efficiency. In this case, a decrease in overall device efficiency may result from wear and tear of a particular component, or from the accumulation of biofouling on critical areas such as turbine blades. These two scenarios require different management responses, but without more information, selecting the correct management response is challenging.

2.5.2 Benefit 5

A biofouling sensor correctly located on critical components of an offshore renewable energy device could report the biofouling condition status of a component at regular intervals or in real time. This information would assist the operator in establishing whether a decrease in device efficiency was a result of mechanical failure that warranted retrieval of the device, or simply the accumulation of biofouling that would either require in-situ maintenance or could be accommodated until the next planned maintenance period.

2.6 Summary of Benefits

Application of Biofouling Sensor Technology	**Benefit to Renewable Energy Industry**
1a: Measure biofouling levels on key components of offshore renewable energy devices to decrease health and safety risks	Provide a real time data stream to inform operators of maintenance requirements, reducing the need to employ commercial divers in highly dynamic environments.
1b: Measure biofouling levels on key components of offshore renewable energy devices to decrease maintenance costs.	Provide a real time data stream that would inform operators of the optimum time to conduct maintenance based on real biofouling levels rather than expected or predicted levels.
2. Indicate threat to data quality from instruments and provide mitigation options	Measure biofouling in the proximity of a particular instrument and inform the operator when biofouling of a critical threshold occurs. This would allow the operator to either schedule maintenance in sufficient time to ensure a genuine data stream, or be clear about when data quality from the instrument is compromised.
3a: Increase efficiency of survey operations	Allow device operators to understand how much biofouling removal is required prior to survey work and thus inform likely asset management costs and maintenance time scales
3b: Increase efficiency of survey operations	Provide the option of conducting biofouling management during other routine operations at regular intervals to reduce the time required from high cost, specialist contractors
4: Reduce the risk of colonisation by non-native species and protect against prosecution.	Differentiate between microfouling and macrofouling, and therefore predict the risk of species of concern occurring on a device.
5: Trouble shoot loss of device efficiency and inform management action	Assist the operator in establishing whether a decrease in device efficiency was a result of mechanical failure that warranted retrieval of the device, or simply the accumulation of biofouling that would either require *in-situ* maintenance.

3 Selection criteria for Biofouling Sensors

3.1 Assessment criteria for technology review and future sensor requirements

In order to assess the feasibility of conducting a biofouling sensor development project, it was first a requirement to understand which technical detection criteria would be required of a suitable sensor. It was also a requirement to determine the assessment criteria that would be used to assess the sensor technologies discovered during a literature review.

To achieve these aims, prior to a technology review, an industry consultation exercise was carried out via a detailed and targeted survey to attempt to define which physical parameters of biofouling assemblages are required by a biofouling sensor targeted at the offshore renewable energy sector.

The results showed that the offshore renewable energy industry has differing requirements depending on the type of energy extraction technology concerned. It was also apparent that many developers have limited deployment experience as the industry is still in its infancy. Actual deployment times acheived to date are generally short, meaning that experience of issues arising from long-term deployments is limited. Therefore, in addition to stating requirements indicated by developers we have also included selection criteria that have become apparent to us during our extensive involvement with biofouling and other more established marine industries.

Requested requirements by users	**Recommended requirements of scientists**
Thickness of biofouling	Economic viability
Digital visual image capture	Remote access
Density of biofouling	Low maintenance requirements
Conductivity impedance	Real time data acquisition
Location of biofouling	*In-situ* data acquisition

Table 1: Summary of a biofouling sensor requirements from users and scientists.

3.2 Physical requirements

The consultation phase suggested that device operators anticipate that physical surveys of devices were the most probable method of monitoring biofouling. However, the cost of visiting and surveying devices in tidal streams is substantial and may well not coincide with peak settlement patterns for the most efficient use of resources.

If a sensor was to be developed, the ability to quantify biofouling thickness and composition was identified as the most important feature by developers. The sensor would also need to be able to detect biofouling on specific areas that would be particularly detrimentally affected by biofouling, such as rotor blades, other moving parts, and connectors. The ability to monitor architecturally complex components and different materials are therefore also important selection criteria.

Ideally, biofouling sensors would need to incorporate capabilities that will indicate volume, extent, exact location and type (i.e. organic, inorganic) of biofouling in order to determine the best course of mitigation action. Optimal solutions would work in-situ, in real-time, without the need of specialist expertise or cost prohibitive financial outlay, and be capable of performing for long durations with minimal maintenance and a reasonable degree of accuracy. In the case of off-shore renewable energy devices, they would also have to withstand extreme conditions underwater in terms of peak flow velocities and collisions with water borne debris. No biofouling sensors have been found that meet all these demanding criteria, but section 4 is a synopsis of technology used in other water-based industries that may offer possible starting points for the design of suitable monitors for the offshore renewable energy sector.

4 Technology Review

4.1 Introduction

In this section existing or novel technologies that are either already commercially available, or have been developed for use as biofouling sensors to monitor the growth of biofouling in aqueous systems or structures are reviewed. There are no technologies specifically available to monitor biofouling growth on offshore renewable devices which operate in highly dynamic environments. Comparable marine industries that are also susceptible to the effects of biofouling have been investigated to gain an understanding of available and researched technology that may be adapted for use on marine energy devices.

There is a wide range of industries that require biofouling sensors and they vary significantly in financial value. There have, therefore, been many attempts to develop suitable technologies and consequently this review may not be exhaustive but concentrates on the most relevant products and research to date.

Finally, the most suitable of these existing technologies to take forward have been identified, based on a range of selection criteria (See Section 8), for potential development into fit-for-purpose biofouling sensors for offshore renewable energy devices.

4.2 Biofouling sensor background

Most conventional methods to detect or sense biofouling are designed for operations where physical access to the structure being monitored is possible, either with the use of in-line sampling or the removal of specialist segments. A common method is the use of removable in-line structures or 'coupons', which are allowed to foul for a certain period of time and then removed and analysed destructively (see Robbins Device, Ruseska et al. 1982).

This method offers a representative sample that can be used to extrapolate fouling levels based on a single sample. It can also require time consuming analysis using specialist techniques. Alternatively, deposits can be scraped and removed manually from fouled infrastructure for subsequent laboratory analysis, again using specialist techniques. The obvious drawback to both of these techniques is that any regular physical access to an off-shore marine device will, in all likelihood, be impractical. By far the most preferable option to monitor fouling would be the use of sensors that provide remote access to all the information required.

Microfouling sensors designed to detect biofilms comprised of microscopic organisms such as bacteria and diatoms (also referred to as 'microfouling') have received extensive attention. This is because of human health issues in water treatment and food processing plants increased operational and cleaning costs combined with decreased efficiency in cooling systems and heat exchangers and other water based heavy industries. Techniques include the measurement of light scattering, turbidity, electrochemical impedance, vibration response of the monitored surface and diffusion limitation. Sensors for macrofouling (larger, sessile multicellular organisms) have not received as much attention and treatment is generally based around attempts to prevent fouling, with biocidal or foul-release coatings, wipers, filtration or periodic and costly mechanical cleaning.

This review covers selected experimental and commercial technologies, but is not exhaustive as not all biofouling sensors technologies encountered were considered potentially transferrable to applications on offshore renewable energy devices. Internet searches were performed using the National Marine Biological Library and Google Scholar for research papers, specifically targeting journals such as “Biofouling” for both macro and microfouling, and general internet searches were undertaken to look for commercial technology using search terms such as “biofouling”, “fouling monitor”, “fouling sensor”. Also some companies were contacted directly via contacts made at industry conferences. Technologies are separated by their applicability for detecting macro or microfouling, and cover published scientific research as well as available commercial products. Technical details describing specific modes of action are frequently not available for commercial equipment, however where available the relevant published scientific literature and references to texts have been provided.

4.3 Macrofouling: Scientific studies

4.3.1 Field techniques

The simplest method of monitoring macrofouling is with the employment of marine scientists specially trained and experienced in characterising fouling assemblages. The use of visual surveys, settlement plates, plankton net sampling (to determine early presence and propagule presence of species with planktonic larval stages) and in-situ monitoring ROV, diving, close-up underwater photography) can all be used to parameterise the extent of biofouling on a structure together with the risk of biofouling occurring (Hodson et al. 1995). Questions such as which organisms are present, how fast the assemblage is growing, where vulnerable locations are on the device and effectiveness of any treatments can all be answered by a fouling taxonomist.

Whilst extremely accurate in terms of assemblage identification and semi quantitate analysis that far outweighs any mechanical monitoring system, a drawback lies in the requirement for specialist personnel. Additionally, this approach can sometimes require considerable time although simple analysis through periodic image capture, by ROV, diving etc, can yield cost effective results in some circumstances where simple changes in spatial and temporal fouling levels are required.

4.3.2 Computer image processing and automatic counting and measuring of fouling organisms

Attempts have been made to write computer scripts that enable digital scoring of fouled panels from high quality photographs. Potentially, if in situ images (i.e. underwater) could be transmitted to such a computer system, threshold levels could be allocated to advise on cleaning regimes. Only one scientific paper was found that detailed a computerised process, written in 1991, which details the mixed results of the experiment. While the process was significantly faster than scoring panels by eye, problems were found in detecting where one organism ended and another started in some phyla. No evidence could be found of more recent research into this area with more powerful computer and imaging capabilities.

In situ quantification of fouling on fish cages using underwater photography and image analysis has been trialled as far back as 1995. It was noted that the various depths, sides and rows of cages differ in fouling levels and so sufficient sampling areas need to be used to gain an accurate reading. Wright et al. (1991) noted three critical factors for effective use of computers to quantify fouling levels: sufficient contrast between substratum and fouling, homogeneity of colour texture of the substratum and the absence of light reflection during image capture to gain the best image contrast. While this might seem a problematic list of necessary factors to achieve, image technology has undoubtedly improved vastly since 1991 and imaging software that does not require such exacting factors will probably exist. In Hodsons et al. (1995) fish cage experiment they stated that even 20 years ago they were able to take large numbers of non-destructive 'samples' from fish cages that could be analysed quickly providing a permanent record of fouling and identification of dominant species to be identified and counted. The method did require images to be taken at fixed distances from the structure and with a blue background that could be cropped from final images prior to analysis. Images were scanned into a computer, enhanced and analysed by measuring the amount of remaining open mesh in the nets surrounding the cage i.e. measuring areas unfouled rather than fouled. They were able to identify the dominant fouling species and quantify levels of fouling using this technique.

Digital processing techniques have been employed for other applications such as cell counting in blood samples where a high resolution image is created and cells are tagged and counted.

Image analysis and counting has also been used in human crowd density estimation where several techniques are possible, including one where an image of the original background (i.e. the venue being monitored but potentially the offshore renewable energy subsea structures) is taken as a reference point and, at the point in time of interest, a second image it taken where the background is removed by referring to the original image and the people (or potentially the fouling) can be quantified with image analysis software. Both these techniques are obviously far from the requirements of an offshore renewable energy device, but offer a basis for the technology.

4.3.3 Structure from motion (SfM) as an in-situ tool to measure hydrodynamic loading on fouled structures

This technique makes use of a digital technique that allows the interpretation of 3D structure from overlapping photographs and can potentially be adapted to estimated key characteristics of a biofouling community. The SfM technique can be used to obtain a sparse point cloud from a collection of overlapping photographs which could be taken by ROVs.

This approach relies on matching unique features in images taken from differing viewpoints. In this way the surface can be digitally recreated from a set of photographs. This is a passive technique that does not require complex sampling equipment but utilises ROVs already employed for inspection to take the images and compares these to Computer-Aided Design (CAD) drawings of the device to give a more accurate estimation of biofouling coverage (Macleod, 2013). Surface reconstruction characteristics such as roughness can also be estimated, giving valuable information on drag and added mass coefficients. This technology offers great potential but is limited however in its ability to estimate volume, but not density, of the assemblage. The consultation phase conducted prior to this report suggested both roughness and density are requirements of a sensor for use on offshore renewable energy devices.

Figure 2: A reconstruction of a biofouled underwater structure using Multiview photogrammetry techniques © Andrew Mogg, The Scottish Association for Marine Science & National Facility for Scientific Diving.

Other software is available, as are other methods to create 3D point clouds of underwater structures. Teledyne BlueView has developed an advanced 3D acoustic multi-beam scanning sonar that has reduced sensitivity to water quality and light attenuation providing extremely high resolution underwater images. The technology requires some experience to operate but the company offers comprehensive training, and it is currently being used successfully in offshore oil, gas and renewables industries worldwide. Unfortunately at the current time it is probably cost prohibitive for the offshore renewable energy industry in the context of a biofouling monitor.

Figure 3: Image from www.blueview.com Teledyne Blue View illustrating the quality of images.

4.3.4 TSC ACFM marine fouling probe-Ashtead technology

This Marine Fouling Thickness Gauge takes spot measurements of the thickness of fouling communities using alternating current field measurements (ACFM), an electromagnetic technique. It can be used in situ by a diver or mounted on an ROV. The probe is pushed against the fouling mass, held for a few seconds and a reading is taken via a top side monitor. This can be repeated as many times as is required and practical. The software records all sensor readings, converting them to lift-off distances and storing them in a Windows file.

This approach is likely to produce accurate thickness data but has obvious limitations by not measuring the other descriptors of biofouling required by the selection criteria such as density and roughness. Additionally, this technology requires manual operation and therefore would not be practical for measuring large surface areas of a device in high energy environments. As the offshore renewable energy industry move towards array scales a practical biofouling sensor would require remote operation to be able to provide measurements on multiple areas of multiple devices.

4.3.5 Fibre optic devices

Fibre optics can be used several different ways in relation to sensing of biofouling. Some technologies take advantage of a continual light source being deflected by fouling organisms to measure deposition. This method is in situ, non-destructive and taken in real time (Wong et al. 2003). There are patents in existence which describe technologies using this technique such as an interferometer-based real time early fouling detection system (US7428055 B2, Zribi et al. 2008) in which a fibre optic cable communicates with a light source and a photo detector and uses an interferometric spectrometer. Alternatively, they can be used to measure salinity levels, temperature and flow rate which in turn act as an early warning signals in vulnerable systems. Researchers at the Electron Science Research Institute at the Edith Cowan University in Australia are working on the latter and hope to develop a low-cost, low-power, multifunctional sensor network of real-time monitoring these parameters. As yet, no work has been published.

4.3.6 Pressure drop micro and temperature transfer

This is a simple method where pressure is measured at the inlet and at the outlet of a heat exchanger or other flow through system. Fouling reduces the pressure at the outlet point and so continual monitoring can be used and mitigation employed when pressure drops below a defined critical level. It can be combined with temperature and heat transfer measurements in processes where temperature levels of the product are critical. Other parameters such as heat flux, heat transfer coefficient and thermal resistance are also employed to monitor fouling. These methods are crude and lack sensitivity to fouling levels or the ability to determine exact locations of fouling. However, they do give crude measurements that may have use for monitoring heat exchangers in ORE devices that have been noted as an area of concern.

4.4 Macrofouling: commercial technology

4.4.1 KEMA biofouling monitor

Developed by KEMA, now DNV GL, this bypass loop system was designed as a direct and continuous monitor of larval settlement and fouling growth in water intake (cooling) systems in power plants and off-shore installations. Effectively acting as a duplicate to the biofouling patterns within the cooling system, an up-welling flow of in-take water is passed through four PVC ‘riser-tubes’, via a sedimentation trap towards a pressure free outlet (see González et al, 2012, Bruijs & Jenner, 2012 and Claudi et al. 2012)

The settlement occurs on four ‘fouling plates’ that are placed in the riser-tubes (see Figure 5), and these are sampled at regular intervals to give a real-time fouling figure of n/m^2. The unit provides optimal conditions for settlement of fouling organisms, therefore providing a ‘worst-case scenario’ picture of the fouling situation of the system. It is relatively inexpensive, requiring little maintenance and simple installation and operation procedures, added to which it is already a proven technology being employed in industrial plants in Europe, the Middle East and Pacific Asia.

Figure 4: DNV GL / KEMA monitor

Figure 5: DNV GL / KEMA monitor- PVC riser tubes and fouling plates

4.5 Microfouling: commercial technology

4.5.1 Process Instruments' "BioSense" biofilm monitor

The BioSense monitor is a commercially available monitor for cooling towers and water treatment circuits. A titanium version is also available for specific use in seawater. The controller applies a potential between the probe electrodes that encourages microorganisms to settle and grow on the surface of the probe in preference to settling on the surfaces of a pipe or a vessel. The biological activity of the biofilm creates a signal which the BioSense controller collects and continually monitors. An increasing trend in the signal indicates the onset of biofilm activity on the probe.

The controller can then take mitigation action automatically by, for example, increasing or decreasing the biocide levels. Currently there are three versions of the BioSense that have different levels of sensor capability, date logging, remote access and corresponding price range.

Figure 6: Close up BioSense probe showing developing biofilm.

Figure 7: Close-up of BioSense monitor

4.5.2 Differential turbidity measurement (DTM)

Flemming et al. (1998) and Klahre and Flemming (2000) exploited changes in turbidity measurements to examine growth of fouling organisms in an in-line system. Using two identical turbidity measuring devices, one which was cleaned continuously and one which was allowed to foul, the differential signal between the two devices provides an indication of fouling growth, termed the differential turbidity measurement, or DTM. This allowed for continual real-time, in situ monitoring, with no expert skill or cost requirement after the initial outlay for the devices and could also be fitted to areas that were difficult to access.

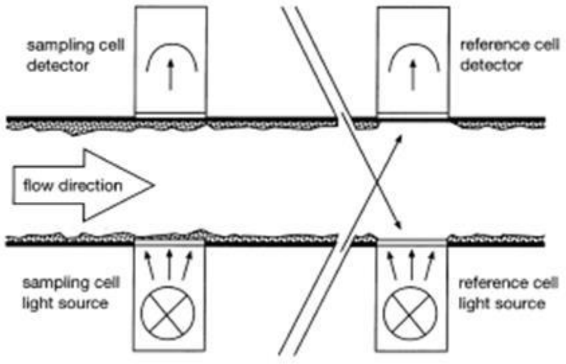

Fig. 1. Schematic depiction of a differential turbidity measurement device.

Figure 8: Schematic representation of a Differential Turbidity Measurement device (taken from Klahre & Flemming , 2000).

4.5.3 ALVIM biofilm monitoring system

The ALVIM biofilm monitor is a real-time, on line, system used in industrial water systems, water tanks, heat exchangers and reverse osmosis membranes. It is able to detect bacterial settlement at a very early stage (down to 1% of surface covered by microorganisms) by measuring the electrochemical activity of the biofilm in proportion to the surface covering. Based on this data it can then manually or automatically adjust and optimize water treatments / biocide treatments, etc.). ALVIM sensors have been already used, with highly satisfactory results, in several industrial fields (cooling water systems, industrial water treatment, desalination, food & beverage, paper mills, etc), including large international companies like Total, GDF Suez and Danone.

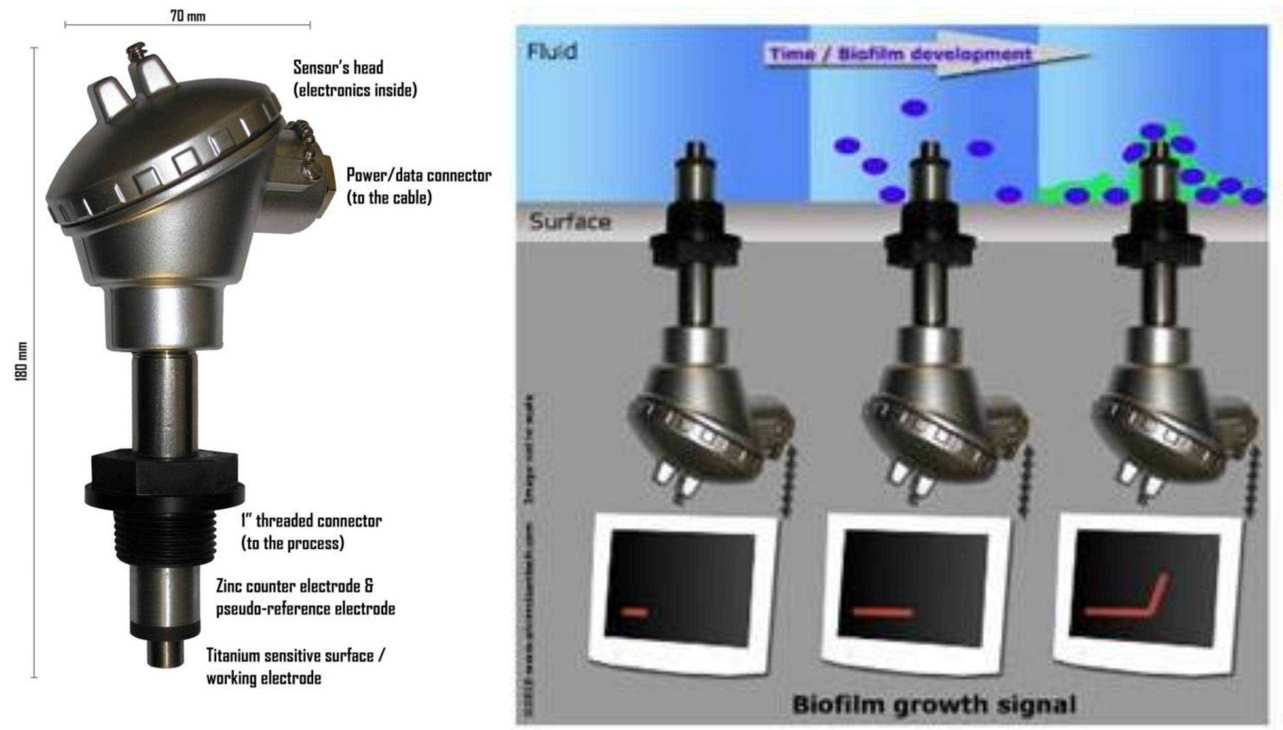

Figure 9: ALVIM Biofilm Monitoring System

4.5.4 Orchidis Laboratoire

The FS series of monitors can be used in-line or by-bass, primarily for use in cooling towers, heat exchangers, filtration and membranes, water treatment and pulp and paper industries. It offers real-time continuous in situ - monitoring, claims to be resistant to harsh environments (land based) and requires no maintenance. The probe itself is rated to work from <1°C to 80°C, and up to 20 Bar pressure. The Skidsens probe is designed for the same industries, but for water systems fitted with a by-pass monitoring and/or control system.

Figure 10: Skidsens probe

Figure 11: FS Series

4.6 Microfouling: Scientific studies

4.6.1 Oxygen sensing optodes

Just in press at the time of writing, Farhat et al. (2015) have produced oxygen sensors for membranes in reverse osmosis and nanofiltration systems. Acknowledging that the commonly used Pressure Drop (PD) measurements (simply a measurement that detects a drop in flow pressure due to a build-up of fouling) to monitor biofouling in these systems was often erroneous (giving false positives) they claim that their oxygen sensing optodes are specific for biofilms and may also register the presence of biofilms earlier than using PD.

The system works by mapping the two-dimensional distribution of O2 concentrations and O2 decrease rates in the membrane where biofouling occurs. Their results showed that the sensors picked up biofouling at an early stage and before an increase in PD was detected. The optodes can also reportedly detect spatial heterogeneities in fouling at a micro scale which can be used to better understand exactly where 'hotspots' might be and lead to more effective mitigation strategies.

4.6.2 Specific oxygen consumption rate

In a similar vein to Farhat et al. (2015), Kappelhof et al. (2003) studied the feasibility of specific oxygen consumption rate to detect biofilm activity in membrane systems and hoped to follow the research with an apparatus and protocol. It is unknown whether this was achieved and no evidence of a prototype device can be found.

4.6.3 Optical sensors

Strathman et al. (2013) developed an optical online sensor superior to previous models, combining measurements of fluorescence, scattering, transmission and refraction in one sensor. Fluorescence, where various chemicals are used to cause excitation in molecules, can detect differing molecules and measure viability and cell growth of biomass. Scattering patterns can distinguish between organic and inorganic fouling. This system is primarily designed for use in drinking water, heat exchange systems, food and beverage processing and the production of washing machines and other water consuming industries. The authors do acknowledge that detection limitations occur then the light transmission through water is restricted, for example in high sediment loads.

4.6.4 Coaxil stub resonator

Hoog-Antonyuk et al. (2015) have recently developed a biofilm sensor which can discriminate between the first and late stages of biofilm growth (characterised as separate, individual spots in early stages, developing into a homogeneous biofilm at later stages). Using an electrical stub, the resonating signals can be measured and analysed and results indicate that early stage and late stage biofilm produce differing identifiable signals. The design is a relatively simple but robust, flow-through model which would be used as an inline microfouling sensor.

4.6.5 Optical fibre sensor using intensity modulation and image analysis

Philip-Chandy et al. (2000) have developed an on-line sensor for closed-loop water processing systems. Using a plastic optical fibre with the cladding removed over a sensitised length, the sensor measures biofilm growth by evanescent field attenuation and intensity modulation as the biofilm develops. The developing biofilm is captured on a charge-coupled device (CCD) camera which records the far field modal distribution of the fibre.

4.6.6 Ultrasonic sensors

Ultrasonic, and indeed vibrational biofouling sensing methods, often employ the 'time of flight' measurement, i.e. the time it takes for a signal to travel from one point to another, together with signal amplitude and temporal behaviour such as damping. Fouling disrupts the signal giving an indication of the level of growth. However, most current technologies of this type appear to require 'canary cells' which are small sensing cells where the measurements are recorded.

This poses a challenge for operation on ORE devices as the biofouling sensing data recorded on such a limited spatial scale is unlikely to be representative of the wider structure. Additionally, the sensing cell itself is likely to be preferentially settled on by larval stages of fouling organisms that often actively seek out this type of space on which to settle and metamorphose into the sessile adult stage, potentially producing false positive results.

Kujundzic et al. (2008) used ultrasonic reflectometry to monitor biofilm formation in a non-invasive real-time manner. The sensor was able to detect presence or absence of a fouling layer. However, the authors acknowledge that additional information regarding the onset, chemical nature and thickness of fouling would be of great value to optimise management of the system.

4.6.7 Clean Ship Project - Royal Institution of Naval Architects

This project was a pan-European consortium studying the effectiveness of a deployment of long range ultrasonic plate waves which travel throughout the entire ship's hull below the water line. The design was developed to prevent or slow down fouling but is also anticipated to act as a continual monitor allowing early detection and aid cost effective mitigation. The system works by continually monitoring the attenuation changes of pulsed waves caused by biofouling growth which are interpreted to detect fouling. As yet, literature does not appear to have been published on the success or otherwise of this device and efforts to contact consortium members have so far been fruitless. The consortium was due to conclude in 2014.

4.7 Ability of reviewed technologies to meet development requirements

Industry representatives were consulted about requirements for a biofouling sensor via an in-depth survey prior to this report to understand the functions that would be required of such a technology. They identified a measure of thickness of biofouling as the primary requirement, followed closely by the provision of a visual image. Some operators also stated that a measure if conductivity and identification of the location of biofouling would be beneficial. The industry is relatively young however, and so additional functions and requirements expected by scientists with experience of fouling in the offshore sector were also included, these were economical viability, remote access low maintenance requirements and real-time, *in-situ* data provision.

Each of the reviewed technologies has been rudimentarily scored for its ability or inability to perform a particular function or service (see Table 2). For some technologies the information was not available, and so a question mark has been marked against the particular issue and technology.

In general, technologies designed to monitor macrofouling, (excluding the use of a trained person on site) and microfouling could all provide real-time *in-situ* data, and were economically viable, as can be evidenced by the use of these systems within industry already. Most technologies could provide some indication of the density of fouling, but the ability to work remotely generally not been included in the design, presumably due to the lack of necessity in the particular industries involved. Table 2 provides a yes/no scoring system for each of the reviewed technologies, where information is available, for its ability to perform the specific requirements as indicated by offshore renewable energy developers and based on in-house experience.

Requested requirements by users	**Thickness of BF**	**Digital visual image captured**	**Density of fouling**	**Conductivity impedance**	**Location of Biofouling**	**Suggested require-ments by scientists**	**Economic viability**	**Remote access**	**Low maintenance requirements**	**Real time**	***In situ***
Ave level of need (1=low, 5= extremely important)	4.7	4.3	2.3	1	(1 comment)		n/a	n/a	n/a	n/a	n/a
Macrofouling: Field techniques	✓	✓	✓	✗	✓ ✗ Depending on method		✗	✗	✗	✗	✗
Differential Turbidity Measurement	✓	✗	✓	✗	✗		✓	✗	?	✓	✓
Fibre optical devices	✓	✗	✓	✗	✗		✓	✗	?	✓	✓
Pressure Drop	✗	✗	✗	✗	✗		✓	✓	✓	✓	✓
KEMA monitor	✓	✗	✓	✗	✗		✓	✗	✓	✓	✓
Microfouling: BioSense monitor	✗	✗	✓	✗	✗		✓	✓	?	✓	✓
ALVIM monitor	✗	✗	✓	✗	✗		✓	✗	✓	✓	✓
Orchidis FS & Skidsens monitors	✗	✗	✓	✗	✗		✓	✗	✓	✓	✓
O2 sensing optodes	✗	✗	✓	✗	✓		?	✗	?	✓	✓

Requested requirements by users	**Thickness of BF**	**Digital visual image captured**	**Density of fouling**	**Conductivity impedance**	**Location of Biofouling**	**Suggested require-ments by scientists**	**Economic viability**	**Remote access**	**Low maintenance requirements**	**Real time**	***In situ***
Specific O2 consump-tion rate	?	?	?	?	?		?	?	?	?	?
Optiquad sensor	✗	✗	✓	✗	✗		?	✗	?	✓	✓
Coaxil Stub Resonator	✗	✗	✓	✗	✗		?	✗	?	✓	✓
Optical fibre sensor w. intensity modulation	✗	✗	✓	✗	✗		?	✗	?	✓	✓
Ultrasonic sensors and SAM	✗	✗	✓	✗	✗		?	✗	?	✓	✓
Clean Ship Projects	?	?	?	?	?		?	?	?	?	?

Table 2: Comparison of reviewed sensor technologies and their ability to meet developer and scientist requirements. (Green tick = technology fulfilled this requirement, red cross = did not fulfil this requirement, blue '?' = unknown) Scores were decided purely from available literature and not from detailed discussions with manufacturers or researcher

4.8 Considerations affecting efficacy of reviewed technologies

If a biofouling sensor is to be operated on an offshore renewable energy platform, the mode of action of the sensor will be required to be compatible with the protective or antifouling coating system on the device. The following table considers the relevant modes of action of the sensing technologies reviewed in this document with different coating systems which provides another selection criterion for determining the applicability of the technology type to the offshore renewable energy sector.

SENSOR TYPE	**METHOD OF DETECTION**	**CONSIDERATIONS FOR METHODOLOGY**
Macrofouling		
Field techniques	Fouling scored by trained lab staff i.e. by eye	Coloured coatings can mislead the eyes. For example slime fouling is easier seen against white coatings than red or brown
DTM (Differential Turbidity Measurement)	Measurement of change in turbidity readings	Turbidity could be affected by coating roughness and change
Fibre optical devices	Measurements of: deflection of light paths from organisms &/or ppt, temp, flow rate.	Release of soluble components from the coating may affect the drift of calibration of these sensors
Pressure Drop	Measurement of pressure differential between inlet and outlet	Coatings may alter this pressure build up with roughness increases or with erosion of coatings.
KEMA monitor	Provides settlement tokens for analysis	Roughness of coatings may provide a change in the noise over time.
Microfouling		
BioSense monitor	Monitors trend of biofilm electrical signal i.e. increased signal= increased biofilm	Changes in the surface/boundary layer conductivity from biocide release, or coating component dissolution may affect the reading given here. Likely to be a calibration or signal/noise issue.

SENSOR TYPE	METHOD OF DETECTION	CONSIDERATIONS FOR METHODOLOGY
ALVIM monitor	Measures electrochemical activity in proportion to surface covering of fouling	Electrochemical activity can be affected by the small molecules released from a coating, or from dissolution of pigments
Orchidis FS & Skidsens monitors	Unknown	
O2 sensing optodes	Maps 2D distribution of O2 concentrations and O2 decrease rates in membrane system where biofilm occurs	Membranes tend to get very rapidly fouled if not adequately protected. Membranes that are protected can be affected by smaller pore sizes etc. when coated. Likely to be a short deployment sensor.
Specific O2 consumption rate	Similar to above-measures specific O2 consumption rates to detect biofilm activity	As above.
Optiquad sensor	Measures fluorescence, scattering, transmission and refraction	These physical aspects of the surface will be affected by pigments and binders. Changes in pigments intensity over time may lead to a drift in sensor accuracy.
Coaxial Stub Resonator	Measures resonating signals using an electrical stub. Differing signals = different stage biofilm	As with other electrochemical sensors above.
Optical fibre sensor w. intensity modulation	Measures biofilm growth by evanescent field attenuation and intensity modulation as the biofilm develops.	Release of soluble components from the coating may affect the drift of calibration of these sensors
Ultrasonic sensors and SAM	Detects presence or absence of a fouling layer using ultrasonic and vibrational methods and 'time of flight'.	May be affected by surface. Ultrasonic may promote detachment of coating which may skew results.
Clean Ship Projects	Deploys long range ultrasonic plate waves along hull to prevent or slow fouling as well as detect growth by detecting changes in pulsed waves.	As above

Table 3: Considerations affecting efficacy of reviewed technologies.

4.9 Technology review conclusions

4.9.1 Potential microfouling sensor technology

Microbial fouling is most likely to pose operational problems to offshore renewable energy devices where it interrupts sensor operation, results in microbial influenced corrosion or simply acts as a precursor to secondary and more mechanically detrimental forms of macrofouling.

Technologies such as the differential turbidity measurements and optical fibre systems could be modified to provide an indication of when microfouling accumulates to a threshold level beyond which an offshore renewable energy device sensor package requires cleaning and or re-calibration.

Microbial fouling sensor technologies that use electrical impedance and a mode of action could also be applied in key areas of an offshore renewable energy device to report general levels of microbial fouling. This approach could have merit where materials might be susceptible to microbially influenced corrosion, such as in semi-enclosed spaces where anoxic conditions may develop. Mitigation measures resulting from detection of high microbial levels could involve flushing of the semi-enclosed space to re-establish oxygen availability.

Many of the microfouling sensors identified by this review rely on having an in-line system in which to test. This renders these systems inappropriate for most applications on offshore renewable energy devices. However, in closed-loop systems where seawater is being used instead of hydraulic fluid, these technology types could be highly applicable.

While ultrasonic sensors have their drawbacks in terms of potential dislodgement of coating systems and requiring significant energy supplies, they are a proven technology for use on ships hulls and are therefore, potentially suitable for adaptation to offshore renewable energy devices. Additionally, these technologies could possibly act in a dual role by means of providing a detection mechanism as well as an active antifouling mechanism for niche areas of a device.

This review was unable to discover a microbial biofouling sensor technology that could be transferred directly into the offshore renewable energy sector. However, many of the modes of action such as the Differential Turbidity Measurement approach have the potential to produce useful information for device developers and operators by indicating when the maintenance of niche areas such as sensor packages is required. The optimum scheduling of maintenance activities based on real time sensor data could provide significant cost savings when the costs of maintenance on an array scale are considered.

4.10 Potential macrofouling sensor technology

The macrofouling sensor technologies reviewed in this document cover a range of modes of action but many of them are not immediately transferable to an offshore renewable energy device. Many technologies reviewed here rely on the ability to capture images of signals from a transducer at a fixed location and rely on the sensing technology itself remaining free from fouling. For example, structure from motion (SfM) technology uses images of underwater structures to compare measurements of fouled structures with measurements of the original structure. The technology type summarised in this report uses images taken by ROV. However, if permanent cameras were mounted on niche fouling areas and fed back to the SfM software, a current and comparable biofouling picture could be ascertained.

The obvious limits to this technology are the need for an underwater camera to remain unfouled and operational for long periods of time to send images to a remote location for analysis. Achieving both of these aspects in-situ for multiple years on an offshore renewable energy device is likely to require considerable further development.

Technologies such as Teledyne Blue View and ADUS Deep Ocean have developed sensitive and high resolution imaging tools such as sonars and multibeam profilers. Although these approaches have the resolution required to detect macrofouling on a device scale, they are likely to be prohibitive due to cost. The mechanical stability of these technologies in tidal stream has also not been established to our knowledge. Again, in terms of long term deployments on offshore renewable energy devices, these types of technologies also rely on lenses and transducers remaining free from fouling in order to detect fouling on the structure of interest.

In summary, there does not appear to be an established sensing technology that can be transferred to the offshore renewable energy device sector that will detect macrofouling within the detection limits defined by our industry consultation phase. Key challenges for sensing macrofouling in this environment, which prevent many of the reviewed technologies from being suitable, include the ability of the device itself to remain free from fouling and the long term mechanical resistance of the sensor in a tidal stream or wave environment. In terms of technology development for the future, a logical area of focus should concern the encapsulation of a macrofouling sensor in a unit that has an inbuilt mechanical cleaning system to enable long term remote deployments.

4.11 Literature review summary

It is clear that no single technology meets the requirements of an offshore renewable energy device biofouling sensor. It also seems likely that any technology developed for microfouling would not be suitable to monitor macrofouling, and vice versa, although this would be an important line of enquiry during discussions with design engineers.

While certain technologies may seem an exciting proposal, such as sonar scanning, a vital consideration that must be a priority has to be cost. In an industry that has yet to become established and where fundamental design is still in its infancy, design costs are a limiting factor for all developers. It would be erroneous at this stage to consume resources on effective technology that is ultimately cost prohibitive to the industry. This is especially the case when developers and operators are required to consider asset management costs on an array scale rather than a single device scale.

Although this review has not discovered a particular technology type that is immediately transferable in the offshore renewable energy sector, the modes of action of several biofouling sensors described in this review offer both the resolution and detection criteria that our consultation phase suggests is a requirement of a fit-for-purpose biofouling sensor for the offshore renewable energy sector, see Table 1.

However, it is clear that technology development is required to bring any of these technologies up to a level where they could provide useful information to the offshore renewable energy industry. Key areas of development required include the long term survivability of the sensor in a mechanically challenging environment and the ability to keep critical areas of the sensor itself free from fouling to ensure reliable operation. These aspects will be incorporated into the following feasibility report which considers the viability of developing a biofouling sensor for the offshore renewable energy sector.

There is also the potential to utilise the knowledge and networking capabilities of CENSIS, (the Innovation Centre for Sensor and Imaging systems based in Scotland since 2013) to harness the expertise of their collaborators. Scotland currently has over 170 companies working on sensor system technologies, generating over £2.5Bn per year and is considered a world leader in this industry. CENSIS works to build collaborations between research and industry specifically in the sensor sector, and their subsea, offshore and marine sector already acknowledges a need for deep-sea sensing technology and is anticipating a need for sensors in aquaculture such as monitors for fish health and pollution levels. Within this vast range of sensor developers, a healthy discussion and consultation could be sought.

5 Sensor functional requirements and feasibility

5.1 Introduction

It is clear from the literature review, at present, no single biofouling sensing technology exists that would meet the requirements of the renewable energy industry. Consequently, development would be required to produce a technology that was fit-for-purpose.

5.2 Sensor requirements

In order to establish the feasibility of a biofouling sensor technology development project and to define the structure of such a project, a prerequisite would be to identify the known challenges where development is required. This step will help scale the project, identify the attributes required from project partners and define the scope of work.

The following section aims to capture the technology requirements defined in the industry consultation phase of this project, combine these with known technology requirements identified from our experience of working in other marine industries and compare them with the state of the art technology in terms of biofouling sensing as indicated by the literature review.

The result is a list of specific areas where technology development and innovation is required to produce a biofouling sensor that is fit-for-purpose for the renewable energy industry. These areas will then be used to suggest the structure of a biofouling sensor development project, if such a project is deemed feasible.

Functional Requirements	Innovation
A sensing technology that is able to sense and measure multiple different parameters of both macro and micro fouling. These parameters include: • Differentiation between micro and macro fouling • Thickness of biofouling • In the case of macrofouling, the type of fouling organism (barnacles, vs algae for example or hard vs soft)	Either a multi-function sensor capable of detecting a range of variables, or a number of different technologies, each designed to detect a specific variable.
Long service intervals of up to 7 years	• Exploration of low energy demand modes of action • Exploration of advanced battery technology

Functional Requirements	Innovation
	• Exploration into the possibility of direct power supply from the device (hard wired) or wireless power scavenging from high voltage cables
Harsh operating environment and high risk of collision and impact damage	Solid state electronics, impact absorbent composite housings and experience from other environmentally demanding industries
Requires a power supply to drive an active antifouling system for the sensor itself	Exploration of range of effect of novel UV LED technology including lamps and UV LEDs embedded in light transmitting silicone sheets
Future proofing so additional sensing capability likely to be required	Capability for modular additions to a main sensing unit to increase capability with a retro- fitted module.

Table 4: Functional requirements and innovation needs of a biofouling sensor technology

Many of the developmental challenges highlighted can be overcome as a result of the rapid development and cost reduction that has occurred in components such as LED technology, battery longevity and composites. The most challenging element is the lack of guidance from the industry in terms of the most useful parameters to measure, which is due to the lack of experience of long-term marine energy device deployments in high energy sites. This knowledge gap can only be addressed by seeking experience from developers as the number and duration of deployments increase in forthcoming years, and incorporating a flexible or modular design that could allow retrofitting of additional sensing capability into an existing sensor platform.

5.3 Feasibility Assessment

The potential advantages of developing a biofouling sensor for use in the renewable energy industry are clear. The benefits of using such a technology are varied, but in general terms the technology would reduce the requirement of in-situ access to a device and would serve to inform the most appropriate time to conduct maintenance, including biofouling management.

Both of these aspects have the potential to save the industry money by optimising the timing and frequency of maintenance missions, potentially reducing health and safety concerns associated with frequent marine operations, as well as providing potential investors with greater confidence about their likely asset management costs.

However, when assessing the overall feasibility of a technology development project, other aspects need to be considered. For example, if the project was to secure investment, a robust business case would need to be presented that demonstrated a likely return on investment at an acceptable level of risk.

At present, a robust business case would be challenging to produce for several reasons. Firstly, it is unlikely that there are currently sufficient numbers of renewable energy devices either planned or in existence to generate a significant return on any development costs. Secondly, the target market is unsure about its current need for such a device to the extent that the design criteria are not defined with certainty.

The points above are undeniable and if the concept of a biofouling sensor targeted solely at the renewable energy industry is considered, the concept seems unfeasible. This is despite the fact that the advantages of using such a sensor are clear and the technological hurdles to overcome to produce a suitable sensor are likely to be achievable.

It is the suggestion of this study that the renewable energy industry will represent a viable market for a biofouling sensor and such a technology will reduce operating costs of the industry. However, this is only likely to be the case after the first developers have struggled to deal with the practicalities of asset management of a full scale array, which is likely to be some years away.

Alternatively, if the concept of a biofouling sensor is considered with the renewable energy sector being one of several target markets including other high energy marine operators such as Oil and Gas, telecommunications, shipping and aquaculture, the project looks highly feasible.

5.4 Feasibility summary

If the concept of a biofouling sensor development project is considered with the renewable energy as the sole target market, the project looks unfeasible. However, if a biofouling sensor technology was developed that was capable of serving the renewable energy industry and also capable of providing the same cost savings to other larger and more developed marine industries such as shipping and Oil and Gas, in the short term, the project appears feasible and potentially highly beneficial and lucrative. This scenario would allow the renewable industry to benefit from such a technology when the industry was advanced enough to require it.

6 Next steps

6.1 Potential project

6.1.1 Structure

The structure of the biofouling sensor development project would be likely to follow the traditional path of a technology development initiative. In this study we assume that a consortium is formed by a mixture of capital investors who cover the costs of project partners who contribute different technical elements to the project in exchange for a licencing fee or royalties produced from sale of the product.

The exact structure of the project could vary considerably and in reality would be determined by both the investors and consortium. The requirement for contracted services such as marketing and legal provisions would vary depending on the in-house capability within the consortium.

Three phases of the project are presented below and consist of: Project Conception, Main Work Streams and Market Readiness Activities. The Project Conception would start first and be immediately followed by the Main Work Stream. Once a predetermined development threshold had been achieved, the Market Readiness Activities would commence and run in parallel with the main work stream.

6.1.2 Project conception

- **Proposal development** – creation of a written proposal to secure interest with potential consortium members and investors. Crucially, this stage should take into account all potential markets as well as the renewable energy sector.
- **Consortium building** – arrangement of the most appropriate consortium to cover the technical and business aspects of developing a new technology
- **Securing investment** – Contracts between consortium members and investors including intellectual property agreements and protection.
- **Project planning** – cash flow and resource planning to include appointment of new personal if appropriate.

6.1.3 Main project work streams

- **Technology review** – expansion of the technology review presented in this study to include patent searches and recent research. Review of recent development of key components such as composite housings, long life batteries, LEDs and wireless power scavenging systems.
- **Laboratory based proof of concept stage** - Development and testing of the mode or modes of action of the biofouling sensor and calibration against known biofouling conditions.

- **Field test - marina** – testing of the most suitable modes of action in a prototype format in a semi-field setting to evaluate the accuracy of the modes of action for measuring real fouling scenarios. This step also provides an assessment of the ruggedness of the unit. Additionally, this stage will determine realistic power requirements for long term deployments together with the effect of natural environmental gradients (salinity, temperature and nutrients) on the detection mechanisms.
- **Refine** – The prototype will require refinement and modifications based on the preliminary marina field trials. The project may cycle through the previous two stages (Laboratory Based Proof of Concept and Field Test – Marina) several times.
- **Field test – instrumented offshore buoy –** this phase provides an opportunity to test the ruggedness of the prototype device whilst still allowing simultaneous environmental data collection and greater ease of access compared to testing on a full scale offshore renewable energy device.
- **Refine –** The prototype will require refinement and modifications after completion of the offshore trials. As with the previous refinement stage, the project may require multiple cycles of laboratory based modifications and field testing.
- **Field test – offshore renewable energy device test platform** – Once a suitable prototype has demonstrated reliable and repeatable results on a relatively easy to access offshore buoy, the next test phase will be on an offshore renewable energy device testbed under real operational conditions.
- **Modification for mass production –** Following successful testing on an offshore renewable energy device platform, the prototype unit will be stripped and re-designed to enable cost reduction of components and ease of assembly and servicing.
- **Field Test - offshore renewable energy device test platform** – A prototype mass produced version will be re-tested on the offshore renewable energy device platform to ensure that the modifications made to enable mass production have not compromised the performance of the technology.

6.1.4 Market readiness activities

- **Marketing** – Conducting a market assessment of the most promising target markets including the renewable energy sector, and development and implementation of an appropriate marketing strategy for each chosen target area.

6.2 Suggested partners

6.2.1 Partner type

The makeup of a successful consortium that would be capable of delivering a biofouling sensor project is likely to consist of the following elements:

- **Funding mechanism –** either private, industrial or public R&D funding (U.K. or National).
- **Established sensor manufacture** - ideally with prior experience of designing and manufacturing sensors for demanding marine environments.
- **Offshore renewable energy device operator or developer –** with previous experience of prolonged full scale offshore renewable energy device operations.
- **Marine research and development facility –** with biological expertise of the biofouling process and access to controlled laboratory conditions and field test sites.

6.2.2 Contracted services

- **Marketing specialist** - with experience of launching novel marine technologies to a wide range of markets.
- **Legal provision -** for Intellectual Property protection.
- **Production consultant** – to provide guidance during the transformation of the prototype unit into a unit suitable for mass production.

6.3 Technology readiness levels

The structure of a project capable of taking state-of-the-art technology and developing it to a point where it could serve the renewable energy industry and other marine industries depends on the input and output Technology Readiness Levels (TRL). For the purposes of this project, the entry TRL level will be assumed as 2 (Technology concept or application formulated), and the exit level TRL will be assumed to be 9 (Actual system flight proven through successful missions / operations), however in reality it is likely that the entry and exit TRLs would be pre-determined by investors in the project.

6.4 Timescales

The time scale required to develop a biofouling sensor technology depends on the entry and exit TRLs, which in turn are likely to be determined by the project funding mechanisms. However, given that biofouling sensors currently exist and the modes of action would not necessarily require development from scratch, we propose that a realistic project duration including prototype testing is 3 to 4 years.

6.5 Predicted project costs

Again, predicting the potential cost of a biofouling sensor development project is challenging due to the large number of unknown elements. These include the entry and exit TRLs, the makeup of the consortium, the range of target markets (including the renewable energy industry) and crucially, the level of technical development required between the mode of action in the novel sensor compared with existing technologies.

However, based on previous experience, some of the costs associated with laboratory based proof of concept testing and field tests and project management costs can be predicted with reasonable accuracy. We estimate that the total project cost would be in the region of £300K, but this figure should be taken as indicative only.

7 Conclusion

In summary, the renewable energy industry could potentially benefit considerably from the development of a real time biofouling sensing technology. The primary benefits of such a technology are:

- Reduced operating costs and health and safety implications through optimised use of marine operations to conduct asset maintenance.
- Greater predictive power of device life cycle asset management costs with the ability to monitor specific areas and instruments.
- Increased efficiency of structural surveys by informing operators of the condition of, and level of biofouling on the device prior to surveys.
- The possibility of complying with current and pending environmental legislation regarding marine non-native species
- Trouble shooting capabilities to determine whether loss of device efficiency is a result of mechanical failure of accumulation of biofouling on components.
- The ability to monitor the performance of different antifouling strategies and improve device protection for the next generation of offshore renewable energy devices.

The technological hurdles required to produce a fit-for-purpose sensor are likely to be achievable if full advantage is taken of recent developments in sensor component technology. However, the current immature state of the renewable energy industry and current market size present two significant problems.

1. Identification of the full design criteria may not be possible to determine as the industry has not been operating long enough to fully understand all the capability it would require from a biofouling sensor.
2. If the renewable energy industry is considered as the sole target market for such a sensor, the current market size is not likely to be sufficient to return investment at a reasonable risk level to satisfy investors.

If a sensor technology was developed that was capable of serving the renewable energy industry as well as other more established marine industries, and incorporated a flexible element into the design to allow additional functionality to be retrofitted, we suggest the project is feasible, potentially lucrative, and beneficial to the environment and to the wider marine industry.

8 Acknowledgements

The authors would very much like to thank the following manufacturers for allowing the use of their images and also for the useful insight and technical information offered: Alvim Srl, GL DNV KEMA, Orchidis Laboratory and Process Instruments and also Andy Mogg of the Scottish Scottish Association for Marine Science & the National Facility for Scientific Diving for the use of his Multiview photogrammetry image.

References

Bruijs, M. C. M. & Jenner, H. A. *Cooling water system design in relation to fouling pressure*. Operational and Environmental Consequences of Large Industrial Cooling Water Systems.

Claudi, R., Jenner, H.A. & Mackie, G. L. *Date Monitoring: the underestimated need in macrofouling control.* In: Operational and Environmental Consequences of Large Industrial Cooling Water Systems.

Flemming, H-C., Tamachkiarowa, A., Klahre, J. & Schmitt , J. (1998) *Monitoring of fouling and biofouling in technical systems.* Water Science and Technology. Volume 38, Issues 8–9, Pages 291–298

Farhat, N.M., Staal, M., Siddiqui, A., Borisov, S.M., Bucs, S.S. & Vrouwenvelder, S. (2015) *Early non-destructive biofouling detection and spatial distribution: Application of oxygen sensing optodes*. Water Res. 2015 Jun 11;83:10-20. doi: 10.1016/j.watres.2015.06.015. [Epub ahead of print]

González, J. A., Polman, H.J.G., Venhuis, L.P. Bruijs, M.C.M. & van Aerssen, G. (2012) Biofouling Issue, Global Implications and Solutions Linked to Offshore Business. Conference proceedings: Marine & Offshore Renewable Energy, 26-27 September 2012, London, UK. The Royal Institution of Naval Architects. ISBN 978-1-909024-04-5.

Hoog-Antonyuk, N.A., Mayerb, M.J.J., Miedemac, H., Olthuisa, W., Tomaszewskac, A.A., Paulitsch-Fuchsc A.H., van den Berga, A. (2015).Online monitoring of biofouling using coaxial stub resonator technique. Sensing and Bio-Sensing Research. Volume 3, Pages 79–9

Hodson, S.L.,Burkea, C.M., & LewisIn, T.E.(1995) In situ quantification of fish-cage fouling by underwater photography and image analysis. Biofouling: The Journal of Bioadhesion and Biofilm Research Volume 9, Issue 2.

Klahre, J. & Flemming, H-C. *Monitoring Of Biofouling In Papermill Process Waters* (2000). Water Quality International '98 Part 7. Wastewater: Biological Processes.Wat. Res. Vol. 34, No. 14, pp. 3657±3665, 2000

Kujundzic, E., Cobry, K., Alan, R., Greenberg, A.R. & Hernandez, M (2008). *Use of Ultrasonic Sensors for Characterization of Membrane Fouling and Cleaning*. Journal of Engineered Fibers and Fabrics, Special Edition-Filtration, pages 35-44.

Macleod, A. (2013). De-risking structural loading calculations for Marine renewable Energy Devices. NERC Internship Placement Scheme Report.

Offshore Renewable Energy Catapult Report by SRSL, Marine Growth Mapping and Monitoring. Work Package 1 report. Feasibility of Predictive Mapping of Marine Growth, December 2015.

Philip-Chandy, R., Scully, P.J., Eldridge, P., Kadim, H.J., Grapin, M.G., Jonca, M.G., D'Ambrosio, M.G. & Colin, F. (2000). IEEE J. Sel. Top. Quantum Electron., 6 (5), pp. 764–772

Ruseska, I., J. Robbins, E. Lashen & J.W. Costerton (1982). Biocide testing against corrosion-causing oilfield bacteria helps control plugging. Oil Gas Journal. 253-264.

Strathmann, M. Mittenzwey, K-H., Gert Sinn, G., Papadakis, W. & Flemming, H-C. (2013) *Simultaneous monitoring of biofilm growth, microbial activity, and inorganic deposits on surfaces with an in situ, online, real-time, non-destructive, optical sensor.* Biofouling: The Journal of Bioadhesion and Biofilm Research, 29:5, 573-583. DOI:10.1080/08927014.2013.791287

Wallhäußer, E. Hussein, M.A. & Becker. T. (2013) Clean or not clean - Detecting fouling in heat exchangers. AMA Conferences 2013. DOI 10.5162/sensor2013/A5.

Wong, Y. M., Scully, P. J., Bartlett, R. J., Kuang, K. S. C. & Cantwell, W. J. (2003). Plastic Optical Fibre Sensors for Environmental Monitoring. Biofouling and Strain Applications. Strain Volume 39, 3, 115-119.

Wright.M., Bakus, G.J., Ortiz, A. & Ormsby, B. (1991) Computer Image Processing And Automatic Counting And Measuring Of Fouling Organisms. Comput. Biol. Med. Vol. 21, No. 3, pp. 173-180.1991

Zribi, A., Shih, M., Song, G., Achuthan, A., Claydon, G.S., Kennerly, S.J., Kishore, K.V.S.R., Zheng, J., Harding, K.G., Xia, H. (2008) Interferometer-based real time early fouling detection system and method. Google Patents. US7428055 B2

Websites:

Alvim: http://www.alvimcleantech.com/cms/en/products [accessed Dec 1st 2015]

Ashted Technology 'TSC ACFM Marine fouling probe': http://www.ashtead-technology.com/rental-equipment/tsc-acfm-marine-fouling-probe/ [accessed Dec 1st 2015]

Orchidis Laboratoire 'Neosens': http://www.neo-sens.com/en/products/p/fouling-systems-fs-2.php [accessed Dec 1st 2015]

Process Instruments 'BioSense Biofilm monitor' http://www.processinstruments.net/products/water-analyzers/biofilm-monitor/ [accessed Dec 1st 2015]

Edith Cowan University, Australia, Electron Science Research Institute: http://www.ecu.edu.au/faculties/health-engineering-and-science/research-activity/research-centres/electron-science-research-institute/projects/past-projects/esri/fibre-optic-sensor-network-for-real-time-water-quality-monitoring [accessed Dec 1st 2015]

DNV –GL KEMA Biofouling monitor: http://www.environmental-expert.com/downloads/kema-biofouling-monitor-276723 [accessed Dec 1st 2015]

Contact

ORE Catapult
Inovo
121 George Street
Glasgow, G1 1RD

T +44 (0)333 004 1400
F +44 (0)333 004 1399

ORE Catapult
National Renewable Energy Centre
Offshore House
Albert Street, Blyth
Northumberland, NE24 1LZ

T +44 (0)1670 359 555
F +44 (0)1670 359 666
Info@ore.catapult.org.uk

ore.catapult.org.uk