Review of monitoring methodologies and technologies, suitable for deployment in high energy environments in Wales, to monitor animal interactions with tidal energy devices.





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Report prepared for contract number **MEFA02/20/21**

Recommended Citation

Clarke, D.R.K.; Bertelli, C.M.; Cole, E.L.; Jones, R.E.; Mendzil, A.F.; Lowe, C.D.; Griffin, R.A.; Robinson, M.T., 2021. Review of monitoring methodologies and technologies, suitable for deployment in high energy environments in Wales, to monitor animal interactions with tidal energy devices. A report produced by Swansea University and Ocean Ecology for Welsh Government. January 2021.

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Acknowledgements

We would like to thank all of those organisations and individuals who took the time to meet and speak with us during the development of this review.

Summary

Context and report purpose

The Welsh Government is supportive of the emerging marine renewable energy (MRE) sector and recognises the key role MRE can play in helping to meet its legal commitments to achieve net zero emissions by 2050. The Welsh National Marine Plan (Welsh Government, 2019) includes specific policies in support of low carbon technologies which deliver sustainable marine renewable energy and social and economic benefits to Wales, whilst respecting the environment and needs of local communities.

MRE developments require a range of consents from regulators to enable the full construction, operation and decommissioning of projects. Before consents can be approved the regulator must carry out several technical assessments, for example an Environment Impact Assessment Consent Decision, a Habitats Regulatory Assessment, and a Water Framework Compliance Assessment to meet legal obligations. A proportionate evidence base is required to underpin these consents and to meet the legal obligations set out in legislation such as the Conservation of Habitats and Species Regulations 2017 (as amended).

The Welsh Government has commissioned a review of current and emerging monitoring tools and methodologies to identify the monitoring technologies which are most suitable for monitoring interactions between key marine animals (cetaceans, seals, fish, and birds) and tidal (stream and range) renewable energy developments around Wales.

Approach

The review has built upon a recent review by Associated British Ports marine environmental research (ABPmer) (2020) commissioned by Natural Resources Wales (NRW). It has included literature review, discussions with equipment manufacturers, leading research groups, developers, Non-Governmental organisations, and consultants.

Species in Welsh waters

The scope of the review includes marine mammals, sea birds and fish.

Practical monitoring techniques differ between taxonomic groups of animals. For example, if we consider marine mammals, cetaceans *Ceatcea*, vocalise and can be detected using passive acoustic monitoring (PAM) techniques, whereas seals *Pinnipedia*, do not vocalise/echolocate, so use of passive acoustics are not a useful method for monitoring all species. Different cetacean species broadcast at different frequencies, with porpoise vocalising frequently, and dolphin species less often. The practical effect of this is that porpoise are readily detected using PAM; while dolphins are more difficult to detect and distinguish.

The species which are most likely to require consideration in Welsh waters are described in Section 5.

Monitoring tools, techniques, and application

The report considers a wide range of techniques currently available for monitoring interactions between marine animals and tidal energy devices. These include visual surveys (for marine mammals and seabirds), the use of aircraft and Unmanned Aerial Vehicles (UAV), eDNA monitoring, optical cameras, passive acoustic monitoring, active acoustics & sound navigation and ranging (SONAR), multibeam SONAR, acoustic cameras, and attachment of animal-borne data loggers to track animal movements.

The discussed methods and techniques have been assessed against functional requirements based on the relevant evidence gaps as identified by Offshore Renewables Joint Industry Programme (ORJIP) ocean energy. The functional requirements we have used are set out in section two of this report.

A summary of the methods recommended in Wales is described in Table 1 with more detailed assessments of each technique available in Section 6 of the report.

Visual observations

Visual observations of marine mammals and seabirds are cost-effective and practical, there are well established survey protocols to investigate presence or absence and to determine relative or absolute abundance within a resource area. Visual observations are not practical for monitoring fish.

eDNA monitoring

eDNA monitoring can identify presence/absence of a wide range of species, with the correct survey design and appropriate validation studies, this method is potentially an effective way of establishing distributions of fish (and the same samples can be used for other species groups).

Optical cameras

The use of optical cameras is limited to daylight hours and in relatively clear water. In those circumstances, optical cameras are a method of choice based on their ability to identify species and to view the direct effect of collisions. Unfortunately, turbidity around Wales is high, limiting their practical application. Nevertheless, consideration should be given to deployment of inexpensive optical cameras alongside other equipment to assist with validation of other techniques when conditions are optimal.

Passive acoustic monitoring (PAM)

The use of PAM is limited to cetaceans, where it is an extremely useful tool. PAM is able to detect the presence and absence of animals, identify species (though with more difficulty for the dolphin species where the broadcast frequencies overlap). PAM can also support abundance or relative abundance estimates although calibration and baseline broadcasts may be needed to adjust for varying efficiency at different tidal states.

For broad scale distribution and movements commercial off the shelf (COTS) tools are available and include C-PODS/F-PODS and SoundTraps at reasonable price (£2.5-£5k per unit). These are mobile devices which can be deployed across large areas in passive monitoring arrays, though site specific trials may be needed to check suitability in high velocity currents and in the immediate proximity of devices because of background noise and practicalities associated with mooring.

Clusters of closely spaced hydrophones (4 in a tetrahedral arrangement) can provide bearings of vocalising animals. It is possible to track 3-dimensional movement of animals reasonably accurately (to within metres) using multiple widely spaced hydrophone clusters to provide range as well. This is not straightforward because broadcasts from the animals are directional, making detection at the same time on multiple hydrophones with sufficient separation difficult. There are also important limitations, notably that background noise from both tidal flow or turbines can interfere with signals, that hydrophone clusters for tracking must be carefully positioned with precise clock synchronisation, and suitable arrangements for processing of data, preferably in real time must be put in place. Range is also limited in the noisy environments around turbines with accuracy declining quickly as range increases. All of these factors are challenging, and for fine scale tracking the technique still requires experienced expert support, both to design monitoring programmes and interpret data.

Active acoustics

Active acoustic devices include single beam and split beam echosounders, multibeam sonar and acoustic cameras. Unlike optical systems they are not limited by light level or visibility and are not seriously affected by suspended solid levels. They are valuable tools for fine scale tracking of targets, but classification (species identification) is difficult unless data are combined with other techniques (including PAM, visual observations, and capture studies).

While these are valuable tools, potential effects on marine wildlife generally and the behaviour of the study species must also be considered and separated from responses to the turbine or turbine noise; behavioural responses to sonar are documented for a number of marine mammals (Ellison et al., 2012; Erbe et al., 2018; Romano et al., 2004).

Single and split beam sonar, such as the Simrad/Kongsberg ES and EK 60 and 80 series packages can identify some fish species and can locate targets at long range. However, they have a narrow field of view, and for fine scale tracking they are often used in combination with other devices. Multibeam sonars, which include acoustic cameras, have a wider field of view, but vary in range and resolution according to frequency, with lower frequency devices such as the Tritech Gemini imaging sonar having a practical range of up to 50m for larger animals, and higher frequency devices Soundmetric Corp Adaptive Resolution Imaging Sonar (ARIS) offering better resolution but shorter range (5-10m) as a consequence of the greater attenuation of high frequency signals in seawater.

There are a wide range of device types available which are summarised in the report.

Tagging

Animal-borne data loggers/tags are extremely useful for investigating detailed movements of a range of species, including seals, birds, and fish. Although some cetacean tagging studies have been undertaken elsewhere in the world, it is not a technique currently adopted for use in British waters.

For seals and seabirds, data storage tags are often deployed which include a Global Positioning System (GPS), depth, pressure, and accelerometer sensors. These can be used to evaluate fine-scale underwater behaviours, including the location of the animal and whether the individual has come into proximity of a marine energy device. Tags are valuable tools for investigating habitat use, displacement, and barrier effects because the location and behaviour of the animal can be reconstructed and compared with environmental data for a given site of interest. The main limitation being that there is usually a requirement to recapture the animal to retrieve the tag and download the stored data. For some larger animals, tags can be equipped to transmit data via satellite, global system for mobile communications (GSM) or by ultra-high frequency radio (UHF) to base stations, reducing reliance on tag recovery to collect data.

Data storage tags can also be used for fish, though their use is even more constrained by tag size and the need to recapture.

For fisheries, COTS acoustic pinger and sensor tags are widely used, and provided representative samples can be tagged from target populations, they can provide quantitative data on availability, duration of presence and behaviour in resource areas. Such tags have a unique ID and are tracked using arrays of acoustic receivers, which can be deployed around developments. These can provide quantitative data to enable population level risks to be assessed and are used in an analogous way to PAM, to accurately locate animal movements in the vicinity of structures.

The main difficulty with reliance on tag-based approaches is that the tagged individuals are not guaranteed to approach an energy device or to be present within a wider resource area, limiting collection of fine-scale information on collision events. However, in that scenario, if sufficient animals from ‘sentinel’ populations are tagged and tracked through their life cycle, and do not approach the devices or resource area, that provides some evidence that population level effects are likely to be limited.

Tagging is a particularly useful approach for monitoring tidal range schemes and given limitations on other options, it is currently an important method for obtaining fine scale data for diadromous fish species.

Blade sensors

Although many devices have sensors fitted to turbine blades, these are only likely to detect collisions between tidal energy devices and larger animals. Difficulties associated with separating these from collisions with debris or noise, together with identification of species, limit their value.

Integrated devices

Discussions with research groups looking at fine scale impacts have emphasised the value of combining data from multiple monitoring tools to enable tracking and classification of targets to species level. For example, combining active acoustic tracking with techniques which can identify species (such as PAM, visual observations or optical camera footage) is probably the best currently available option to secure fine-scale observations of behaviour in the immediate vicinity of devices and to infer potential impacts.

MRE Devices deployments in Wales

Device types

At present 12 tidal stream energy devices are planned for deployment in Welsh waters, described in section 8 of the report. These can be divided into three main categories, surface, mid water, or seabed mounted. The seabed and surface mounted devices employ either horizontally oriented turbines using traditional blades, or hydrokinetic turbines mounted either vertically or horizontally.

Pros and cons of different deployment types

Seabed deployments have several advantages. The device is fixed in place and monitoring equipment can either be attached to or built into the device, with the additional benefits of power supply lines and data links to the shore. Alternatively, mobile monitoring equipment could be deployed on fixed moorings focussed onto the underwater energy device.

There are however significant disadvantages associated with monitoring seabed deployments. These include cost and difficulty of regular access to maintain equipment, data storage and retrieval of data from devices that are not connected to fixed lines, and the cost of deployment including factors such as underwater connectors.

Deployments in mid water (currently limited to the Minesto kite) cause particular problems for monitoring. Midwater devices will occupy distinct locations at different tidal states (ebb and flood), and the device continually moves, adding to the uncertainty of its location. Midwater mounting of monitoring equipment is not likely to be practical because of the risk of interaction between the device itself and the equipment moorings. Seabed mounting is likely to be the most practical option, although comes with other problems of data acquisition (frequent deployments and retrievals), data management and analysis.

Surface mounted devices have a number of advantages for monitoring as the equipment can be attached to the surface support structure with power access and methods to transfer data to shore in real time. However, deploying monitoring packages from a distance to look at the device is much more difficult as both the device and the monitoring package will move on their moorings. Monitoring using devices such as PAM clusters and active acoustic techniques may have to be based on equipment built into and onto the device structure, thereby fixing it in place relative to the turbine. Monitoring data from surface devices may also be complicated by additional surface noise created by wave action and the need for expensive marine grade connections.

Monitoring arrays of devices

In addition to the monitoring tools and techniques suitable for monitoring single and small-scale developments, the review has also considered the potential for MRE to scale up into commercial arrays and the potential ability to monitor interactions between key marine animals and tidal stream arrays. Arrays of MRE devices are desirable from an energy production perspective as they allow economies of scale, however, arrays add some additional concerns, firstly in terms of the potential impact of excluding species from potentially large sea areas, and secondly increased risk of collisions as a result of animals evading one device only to immediately encounter another. For that reason, avoidance and impact data collected from a single device cannot automatically be scaled up and applied to array fields.

COTS PAM, and acoustic tracking receiver arrays can be deployed across MRE array deployment areas to provide quantitative far field information on utilisation and avoidance of areas containing turbines, as well as broad scale movements and behaviour. For cost and logistical reasons, fine scale observations may need to be limited to a subset of operational turbines, possibly monitoring pairs of devices across the area to look at the core of the array field and edge effects. For such deployments, the use of mobile integrated solutions such as the Washington State University Adaptable Monitoring Package (AMP), the FLOWBEC (FLOW and Benthic Ecology) platform or the Sea Mammal Research Unit (SMRU) High Current Underwater Platform (HiCUP) approach may have advantages as they can be deployed in various locations over time if required.

Challenges

Monitoring animals in extreme tidal environments creates a range of challenges, both generic and specific to Wales. Challenges which apply to all deployments include the difficulty and cost of mooring equipment in areas of high tidal velocity, integration of equipment with turbine infrastructure, turbulence and noise around devices affecting acoustic monitoring techniques, and corrosion.

Corrosion is a particularly important challenge; at least two active acoustic deployments are thought to have been compromised by corrosion; at the Ramsay Sound DeltaStream site, and MeyGen. Corrosion can be overcome by careful selection of enclosure materials and anodes but requires careful consideration.

Around Wales, visibility underwater is particularly poor even in summer, thus limiting scope for optical observations which would otherwise be the method of choice for observing fine scale interactions between animals and devices. Biofouling is also a significant issue; based on Swansea University surveys in the Bristol Channel and west Wales, it is desirable to retrieve and clean equipment such as acoustic receivers and C-PODS on a three-to-four-month cycle.

Power and data management is a particular challenge for the collection of fine scale data for seabed mounted devices. While this can be overcome by using moored deployments of integrated packages such as AMP, FLOWBEC or HICUP, there are significant advantages for longer term deployments in mounting equipment within or attached to the turbine structure itself with fixed power and datalinks to shore, such as the monitoring approach at Ramsay sound DeltaStream and MeyGen in Scotland. If this approach is adopted it is essential that monitoring requirements are considered at an early stage of the turbine design to ensure that power and data links are available, servicing requirements are fully considered, and monitoring equipment can be deployed in locations which enable objectives to be achieved. This is important on cost grounds as well as effectiveness of programmes; as an example, the cost of underwater cabling and connections can exceed the cost of the monitoring hardware itself, and effective design can therefore both save money and improve results.

Emerging technologies and needs

For far field assessment, COTS products such as F-PODS, SoundTraps, acoustic tags and receivers and data storage tags, are well developed and can be used. Equipment for fine scale studies such as direct turbine observation is less well developed.

Significant investment (£millions) has gone into the development of devices such as the AMP, FLOWBEC and HiCUP This has paid off and many of the basic challenges such as reliability, system integration, corrosion, local power supplies and data storage have been addressed. These are not yet available as COTS tools, but the direction of travel suggests that they may be available in the next few years. Challenges now focus on the development of tools which can be used to solve target classification and data processing requirements, using both traditional software and Artificial Intelligence (AI) tools.

Classification of observed animals remains a key limitation for many methods discussed in this report, with exemptions of visual observations and tagging.

For sonar-based solutions, as the physical mechanics of the equipment limit range and image resolution (e.g. radio waves are greatly attenuated by water). Systems currently favoured in integrated packages and some bespoke developments, include the combination of Kongsberg/Simrad single or dual beam systems, with multibeam developed by Tritech. The latter appears to be favoured as the most appropriate balance between range, resolution, ease of integration and availability of tracking software.

Recent developments of high frequency tagging systems may also allow acoustic fish tracking systems to be extended to seabirds and seals to develop quantitative data sets. This requires further evaluation.

Recommendations and Strategic Interventions

Preferred methods

Preferred approaches for monitoring animal interactions with marine energy devices in Wales are outlined in Table 1. Unless otherwise stated, recommendations cover both tidal stream and tidal range energy devices; where tidal range differs, this is stated.

Planning and Implementation

There are additional recommendations arising from the discussion which include the need for visual sampling protocols, incorporating monitoring at an early stage of turbine design and operational planning and ensuring maintenance and data management plans are in place.

Strategic Interventions

Based on our conclusions above, the following strategic interventions could be considered and would provide considerable assistance to the tidal energy sector:

Baseline monitoring

These proposals aim to provide data that developers can use for initial assessments and to inform consents, covering presence/absence, relative seasonal abundance, and in some cases abundance or the proportion of populations present.

- A baseline visual observation programme for seabirds and cetaceans covering the resource areas; and run for two years pre-construction could be considered. This would include visual surveys for both mammals and seabirds.

- A strategic eDNA sampling programme for fish (and potentially all species), to create a common baseline data set benefiting all developers, again ideally run over a two-year period.

- The establishment of acoustic tracking arrays, together with sentinel tagging studies to provide better understanding of migration patterns for diadromous fish around the Welsh coast. (see Clarke *et al*., 2021a for detail).

Testing innovative technologies

A number of innovative technologies exist which could be trialled to establish their effectiveness in monitoring near field encounters, including turbine strikes. These include 3D acoustic technologies, ARIS and fine scale acoustic tracking studies using UHF equipment for tracking of fish, seabirds, and seals.

Developing and maintaining expertise and equipment

Building capabilities in the development and operation of monitoring technology and the subsequent analysis of environmental data to develop a centre of excellence in Wales would benefit the MRE sector. This should be collaborative and cross-disciplinary, including, amongst other experts: biologists, engineers, computer scientists and statisticians. This will ensure Wales has a strong platform to develop and grow within this emerging industry and allow knowledge and lessons learnt to be widely shared for the benefit of the MRE sector. This would follow the approach taken in Scotland, where a similar function is provided by Marine Scotland and SMRU.

Table 1. Recommended approaches to monitoring animal interactions with marine tidal energy devices in Wales assessed for each functional requirement.

Species group	Recommended approaches in Wales	Comments
FR1. Presence or absence of a species in the area of development and the abundance or proportions of at-risk species in the resource area		
Cetaceans	Visual surveys, PAM.	Better understanding if used together.
Seals	Visual surveys, Telemetry.	GPS/sensor tags with satellite/radio base station/GSM download.
Seabirds	Visual surveys, Telemetry.	GPS/sensor tags with recapture/radio base station/GSM download.
Fish	eDNA, Telemetry, capture surveys.	eDNA for presence/absence and seasonal relative abundance can be used for other species groups.
FR2. Occupancy patterns, fine scale distribution and behaviour of mobile species in tidal habitats		
Cetaceans	Visual surveys, PAM arrays.	Needs environmental data/models for comparison with behaviour.
Seals	Visual surveys, Telemetry - integrated tags including accelerometer & magnetometer.	GPS/sensor tags with satellite/base station download. Environmental data (as above).
Seabirds	Visual surveys, Telemetry- integrated tags including accelerometer & magnetometer.	Environmental data needed as above. GPS/sensor tags with base station download or retrieval. Environmental data (as above).
Fish	Telemetry, acoustic arrays + acoustic/sensor tags.	Active acoustics could also be considered for some marine species but Species ID not practical for diadromous species.
FR3. Near field interactions including monitoring of avoidance behaviour and collisions. Including frequency, nature, and consequence of near field interactions between mobile species and tidal turbines, evasion responses and rates.		
Cetaceans	PAM, Active acoustics, visual observations + ADCP (integrated tools). Tidal Range: Visual observations and PAM only.	Avoidance can be examined using existing technology. Observing turbine strikes is at or beyond the limits of resolution except optical cameras. Consider optical cameras if water at deployment site has good visibility.
Seals	Active Acoustics, visual observations + ADCP (integrated tools). Tidal Range: Visual observations only + tagging if needed.	As above. Need to link visual observations to target tracks to classify targets and develop classification algorithms as no PAM to ID species.
Seabirds	Telemetry, Active acoustics + ADCP (integrated tools). Visual observations only for tidal range + tagging if needed.	As seals.

Species group	Recommended approaches in Wales	Comments
Fish	Telemetry, Active acoustics + ADCP (integrated tools). Tidal range: Acoustic tagging and tracking, capture surveys.	Active acoustics unlikely to ID species; fine scale acoustic tracking preferred. Arrays needed within the impoundment and around turbine intakes and sluices
FR4. Behavioural data for different species such as swimming speeds (including burst speeds) and depth utilisation.		
Cetaceans	Visual observations, PAM.	Literature, PAM vertical arrays for depth in Resource Areas.
Seals	Telemetry.	GPS/depth sensor satellite or data storage tags.
Seabirds	Telemetry-integrated tags including accelerometer & magnetometer, Active acoustics.	GPS/depth sensor data storage tags with download.
Fish	Telemetry, sensor tags.	Sensor tags for depth data.
FR5. Understanding sensory perception and near field responses to tidal turbines, including the behavioural consequence of noise, to move beyond using audibility as a proxy for behavioural response.		
Cetaceans	PAM, Active acoustics, Visual	Literature, field observations require environmental data e.g., ADCP. Use of play-back turbine noise.
Seals	Telemetry, Active acoustics, Aerial, Visual.	Literature, field observations require environmental data e.g., PAM, ADCP. Use of play-back turbine noise.
Seabirds	Telemetry, Active acoustics, Visual observations.	As above.
Fish	Telemetry, Active acoustics.	As above.

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1. Introduction

Report purpose

Wales has one of the largest tidal ranges and hence some of the best tidal stream resources in the world, with the potential capacity to provide significant energy generation and contribute to both UK and Welsh Government commitments to transition to a low carbon economy. The Welsh Government is supportive of the emerging marine renewable energy (MRE) sector and recognises the key role MRE can play in helping to meet its legal commitments to achieve net zero emissions by 2050. The Welsh National Marine Plan (Welsh Government, 2019) includes specific policies in support of low carbon technologies which deliver sustainable marine renewable energy and social and economic benefits to Wales, whilst respecting the environment and needs of local communities. It also identifies potential Resource Areas (RA) for wave, wind, and tidal stream developments (Figure 1).

MRE is an emerging industry and although some groundwork has been done in Wales to provide a platform for the sector to grow, there is still much to be done in order to understand the potential interactions of tidal stream and tidal range energy devices with marine animals. Collision risk with tidal stream or tidal range turbines is recognised as a strategic information gap for marine mammals, seabirds and fish when assessing the impact of MRE (ORJIP OE, 2020).

While some evidence is emerging (State of the Science Report; Sparling et al., 2020, Tethys website), relatively few marine turbines are deployed and operational and evidence on the extent of far and near field avoidance (or attraction) to turbines remains limited. A key area where evidence remains poor is the likelihood of collisions between turbines and species foraging or transiting through the area, including marine mammals, seabirds, and fish (ORJIP OE, 2020).

The lack of empirical data creates uncertainty about animal interactions with operating tidal turbines, and actual and perceived risk may differ (Copping and Hemery, 2020). This lack of evidence results in precautionary modelling approaches, which may significantly distort estimates of the likelihood of impact by turbine blades or injury. Utilising technology to monitor the impacts and interactions between installed tidal turbines and marine animals, specifically marine mammals, seabirds, and fish is therefore essential to develop the evidence base.

For MRE developments, the consenting process requires baseline monitoring to support regulatory applications, including model predictions. Consent conditions may also require post consent monitoring of key species. This reflects uncertainty in predictions and the need to collect evidence to validate or correct predictions, confirm compliance with legislation, and to build a wider evidence base to inform assessment of future applications.

The Welsh Government has therefore commissioned this review of current and emerging monitoring tools and methodologies to identify the monitoring technologies which are most suitable for monitoring interactions between key marine animals (cetaceans, seals, fish, and birds) and tidal (stream and range) renewable energy developments around Wales.

The scope of this project reviews information on monitoring methods which can collect evidence to underpin the range of approvals required to build and operate marine renewable energy devices. This includes evidence to inform Environmental Impact Assessment (EIA), Habitats Regulation Assessment, Water Framework Compliance Assessment, planning consents and marine licences. The key objectives of this study are defined in the project scope and include:

a) Review existing and emerging monitoring methodologies and technologies deployed globally and, in the UK, (United Kingdom) that can record interactions (including collisions) between key marine species and tidal stream devices. Providing recommendations on the methodologies and technologies most suitable for use in high energy environments in Welsh waters.

b) Provide recommendations for technologies that could be further developed into monitoring methods and identify if there are technologies that can correlate species behaviour and turbine stimuli (e.g., velocity, acceleration, noise, pressure, particle velocity).

c) Identify the types of tidal stream devices likely to be deployed in Welsh waters and recommend the most suitable technologies that could be used to detect near-field and far-field interactions with animals. The effectiveness of the technology should be considered, in addition to the cost of a monitoring programme. Also, consider whether the monitoring techniques differ for seabed mounted, mid-water and surface piercing devices.

d) Investigate the potential scaling up of tidal stream projects from single devices to large scale arrays, providing recommendations on how these could potentially be monitored and any potential barriers.

e) Identify any gaps in our ability to monitor key marine species and provide recommendations for how gaps may be addressed.

f) Included in the review document, produce a table summarising the findings of the review which will easily identify the methodologies and technologies, their ability, and limitations in monitoring key marine species.

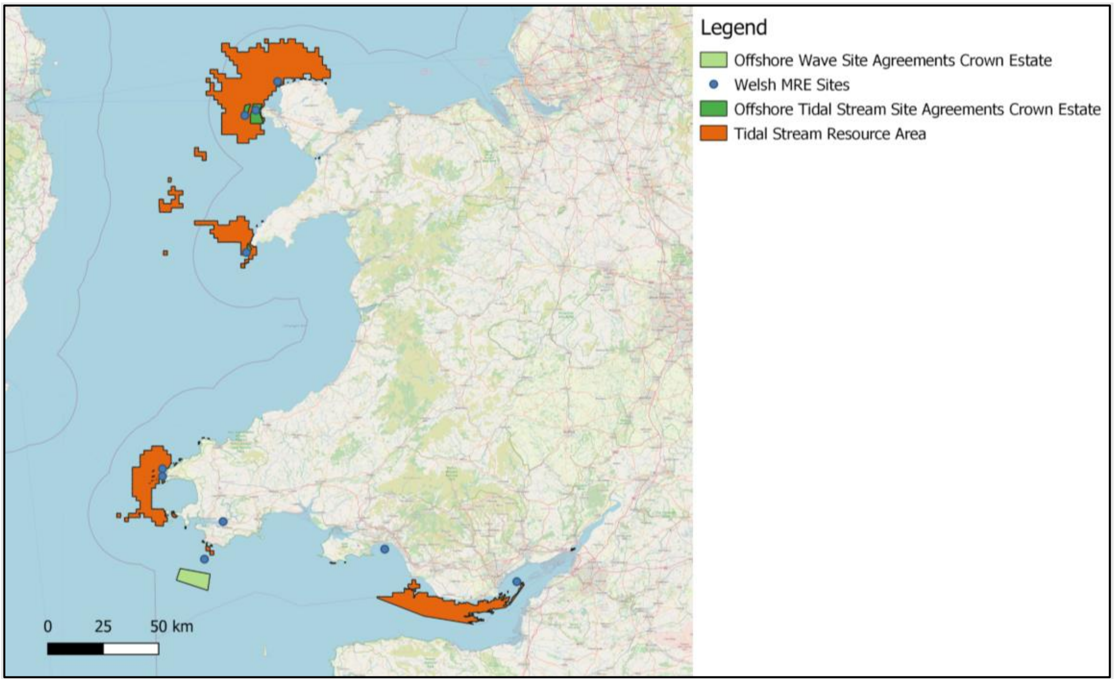

Figure 1. Map of tidal stream energy resource (from LLE portal) with existing and proposed tidal and wave MRE (Marine Renewable Energy) sites and licensed test areas around Wales (data from UK marine energy database and Crown Estate).

Legislative context

MRE developments require a range of consents from regulators to enable the full construction, operation and decommissioning of projects. Before consents can be approved the regulator must carry out several technical assessments, for example an Environment Impact Assessment Consent Decision, a Habitats Regulatory Assessment, and a Water Framework Compliance Assessment to meet legal obligations. A proportionate evidence base is required to underpin these assessments and the necessary consents to meet the legal obligations set out in legislation such as the Conservation of Habitats and Species Regulations 2017 (as amended). For further detail see the NRW website.

Key species of marine mammals (bottlenose dolphins *Tursiops truncatus*, harbour porpoise *Phocoena phocoena*, grey seals *Halichoerus grypus*) seabirds (Manx shearwater *Puffinus puffinus,* great-Northern diver *Gavia immer*, and the red-throated diver *Gavia stellata*) and fish (sea lamprey *Petromyzon marinus*, twaite shad *Alosa fallax*, allis shad *Alosa alosa*, and Atlantic salmon *Salmo salar*) are afforded protection through a range of UK and Welsh legislation such as the Conservation of Habitats and Species Regulations 2017 (as amended), the Wildlife and Countryside Act 1981 and the Environment (Wales) Act 2016, and for this reason developers and regulators must ensure compliance with the legislative requirements of each. Further information on the legislative requirements in Wales can be found here: NRW guidance note.

2. Approach

The approach we have taken to this review brings together existing knowledge from a range of researchers at Swansea University, together with literature evidence and interviews.

The initial web searches underpinning the literature review element of this report were undertaken by ABPmer and NRW. We have complemented that approach with additional work, including searches of the Tethys website, interviews with other academics, equipment suppliers, consultants, and developers, as well as reviews of recent Environmental Impact Assessments undertaken for MRE developments in Wales.

The organisations and individuals we have spoken with are identified in Annex 1.

The structure of this report is as follow:

- Introduction and approach to this review (sections 1 & 2).
- Identification of evidence gaps (section 3).
- Device types and characteristics (section 4)
- Identification of the species most likely to be relevant in assessments of MRE impacts in Wales (section 5)
- Review of monitoring tools and methods and suitability for different species groups (section 6).
- Exploration of costs for different monitoring technology and methods (section 7).
- Discussion and conclusions including challenges, preferred methodologies, effects of different device types and arrays of devices.
- Recommendations (section 9).

3. Evidence gaps

To understand the monitoring and equipment requirements, we need to understand both the decision-making processes and the key evidence gaps. Broadly the decision-making process to define monitoring requirements for turbine interactions can be thought of as a hierarchical series of decisions (Figure 2).

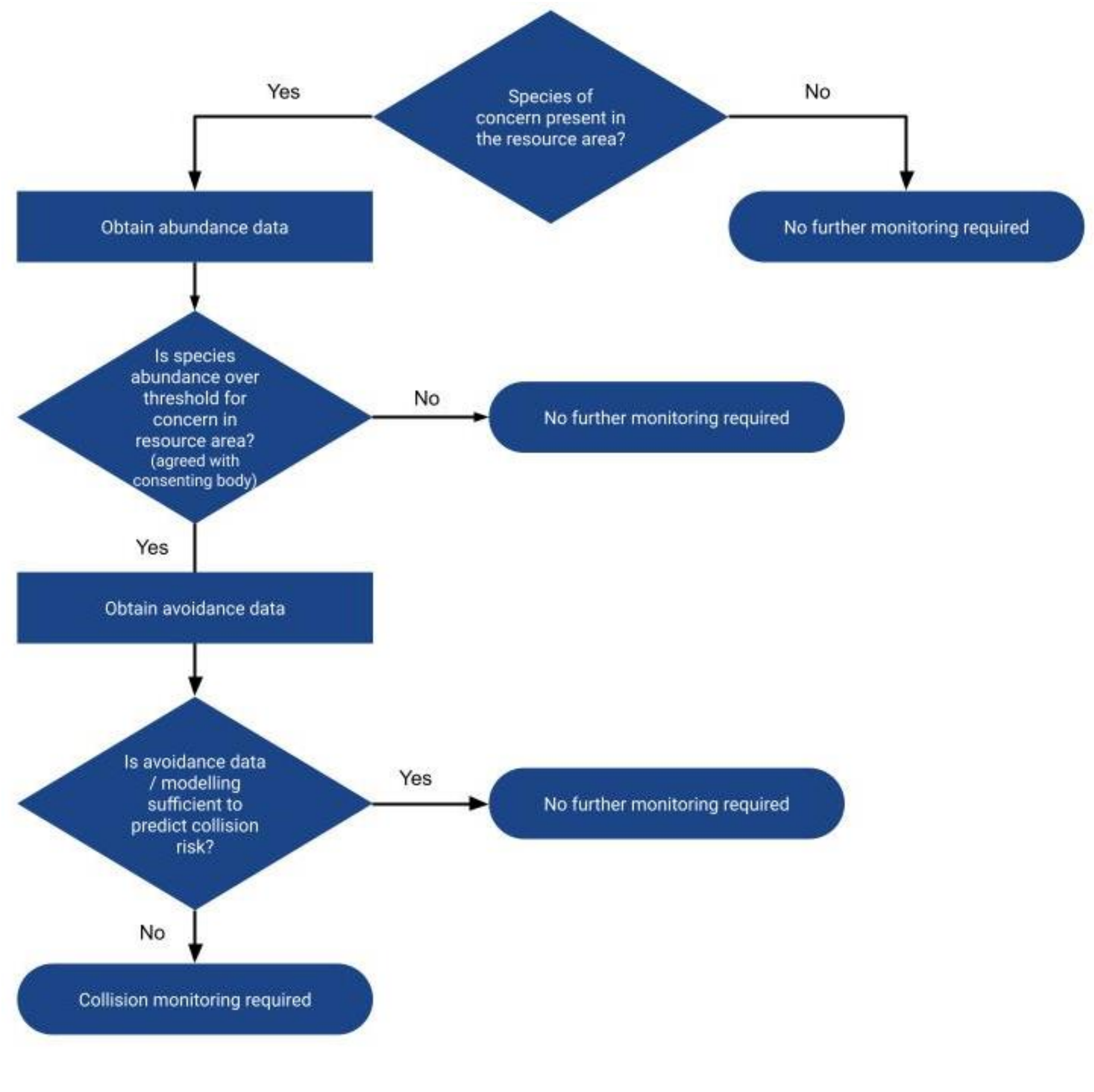

Figure 2. Decision tree for deciding on monitoring needs.

ORJIP OE

The key evidence gaps are linked directly to the decision hierarchy described above and include the lack of strategic baseline data (distribution, abundance, seasonality etc.), avoidance behaviour/rates and collision risk. These align directly with the strategic evidence gaps for marine mammals, seabirds and fish identified by ORJIP OE (2017, 2020). ORJIP OE note that further data on mobile species populations, particularly those qualifying for habitat regulation protection would aid population modelling and the understanding of impacts, improving confidence in EIA/HRA. ORJIP OE (2020) research priorities relevant to the scope of this project, include or imply the following evidence requirements for marine mammals, seabirds, and fish, (see Critical Evidence Needs, Table A1, ORJIP OE 2020). We have expressed these as Functional Requirements (FR):

FR1. Presence or absence of a species in the area of a development and the abundance or proportion of key populations of at-risk species in the resource area.

FR2. Occupancy patterns, fine scale distribution and behaviour of mobile species in tidal stream habitats.

FR3. Near field interactions including monitoring of avoidance behaviour and collisions. Including frequency, nature, and consequence of near field interactions between mobile species and tidal turbines, evasion responses and rates.

FR4. Behavioural data for different species such as swimming speeds (including burst speeds) and depth utilisation.

FR5. Understanding sensory perception and near field responses to tidal turbines, including the behavioural consequence of noise, to move beyond using audibility as a proxy for behavioural response.

Modelling

Given the logistical challenges with gathering marine animal behaviour close to turbine devices in the field, consultants typically use a modelling approach for the various environmental assessments required, following the precautionary principle where data are poor or absent (Horne et al., 2021). Models allow for an estimate of the number of individuals of different species that might collide with a turbine device to be predicted. However, the use of precautionary assumptions may significantly distort conclusions and potentially decision making.

Modelling itself is outside the primary scope of this report and modelling approaches have been summarised by Marine Scotland (2016) and ABPmer (2020). Modelling is, however, important to a consideration of monitoring needs, including avoidance and effects of turbine strikes, as monitoring requirements are in part driven by the parameters required by the different models. The parameters required are important to help identify monitoring requirements in later sections and are summarised in Annex 2.

4. Devices and characteristics

The growing number of devices deployed worldwide, are summarised in Annex 3, adapted from ABPmer (2020), with additional information from the Tethys website. The tidal stream devices currently being considered for deployment in Welsh waters are summarised in Table 2.

4.1. Tidal stream

Tidal stream devices which are planned for deployment in Wales broadly reflect the range of devices deployed more widely and can be grouped into three main types:

- Fixed location devices mounted on the bottom/sea floor.
- Floating turbines, mainly operating toward the surface.
- Midwater devices such as the tidal kite operated by Minesto.

The floating and seabed mounted turbines can be either horizontally oriented 'traditional' turbines, with propeller blades driven by the current flow, or designs with hydrokinetic blades, which are vertically oriented, but with moving blade components in both planes. Annex 4 contains pictures from developer websites to enable visualisation of the different device types.

There are two 'outlier' designs, the Big Moon Kinetic Keel, and the Minesto Tidal Kite.

For the Big Moon kinetic keel, the turbine unit sits on shore, and the energy is created by a vessel which is designed to have a high drag in the water. Energy is transferred to the generator via a cable which turns a drum onshore as the vessel moves toward and away from the land with the tide. As there is no turbine in the water, impacts on the species of concern are likely to be minimal, and we do not discuss monitoring of this device further.

The Minesto tidal kite is a novel midwater device which occupies different spatial areas at different tidal states and speeds.

The Marine Energy Wales (MEW) State of the Sector 2020: Economic Benefits for Wales report highlighted the tidal energy devices that are either currently deployed or have shown interest in deploying in Wales, Table 2 below shows specifically tidal stream devices highlighted in this report.

4.2. Tidal range

Tidal range proposals have been or are being developed for both the South Wales and North Wales coasts. The most advanced of these proposals is the design for the proposed Swansea Bay Tidal Lagoon (Figure 3), where a marine licence application remains under determination. This is a proposal for a pilot scheme, prior to wider deployment of the technology.

Figure 3. A cross section of the Swansea Bay Tidal Lagoon. Image from Tidal Lagoon Power.

In essence, tidal range proposals create an impoundment, or lagoon, with turbine structures embedded in the impoundment wall. Depending on the design, the turbines can be used to generate energy on both flood and ebb tides, with some of the inflow during the flood routed via the turbines, and the impounded water being released during the ebb period via the turbines.

For most of the operating cycle there is a hydrostatic head difference between the impoundment and open water, which drives the turbines. As a consequence, the turbine designs differ to tidal stream energy devices, they tend to spin quicker in addition. Animals passing through may also have to deal with a pressure difference, as well as an increased risk of turbine strike.

Table 2. Tidal stream energy devices currently or to be potentially deployed in Wales.

Developer	Turbine make / model.	Capacity (MW)	Turbine description	Comments re monitoring	Installation date	Planned location
Minesto	0.5MW Deep Green Tidal Kite	0.5MW (increasing to 10MW)	Tidal kite	Moves in all planes. Difficult to observe from a fixed location.	2018 & 2019	Holyhead Deep, Anglesey
Nova Innovation	100KW seabed turbine	0.5MW (x5 100KW turbines)	Bottom mounted standard turbine with blades	Fixed in place can be observed by a fixed (moored) unit.	N/A	Bardsey sound & Morlais demonstration zone
Orbital marine power	O2 2MW floating tidal turbine.	2MW	Turbine blades mounted on spars on a fixed moored surface vessel.	Could attach cameras / active acoustic devices to underside of vessel, or upward looking from seabed.	N/A	Morlais demonstration Zone, Anglesey
Verdant Power	Gen5 seabed turbine	30MW by 2025-26	Seabed mounted traditional turbine with blades.	Fixed in place can be observed by a fixed (moored) unit.	aiming for 2022-23	Morlais demonstration Zone, Anglesey
BigMoon	Kinetic Keel	N/A	Land based generator driven by a vessel attached to the generator by a cable.	Difficult in principle because of vessel movement. Likely to pose less potential collision risk to wildlife as there is no turbine.	N/A	Morlais demonstration Zone, Anglesey
Sabella	seabed horizontal-axis turbine	N/A	Bottom mounted traditional turbine with blades.	Fixed in place can be observed by fixed (moored) unit.	N/A	Morlais demonstration Zone, Anglesey
Instream Energy Systems	Floating array - Vertical axis hydrokinetic turbines (VAHTs)	1MW	Surface platform with sets of hydrokinetic turbine blades operating near surface under the platform.	Mooring arrangements unclear but could be fixed location or moveable.	N/A	Morlais demonstration Zone, Anglesey

Developer	Turbine make / model.	Capacity (MW)	Turbine description	Comments re monitoring	Installation date	Planned location
HydroQuest	N/A	N/A	Seabed mounted unit with 2 sets of vertical blades rotating around a central vertically mounted axis.	Single fixed unit deployed for 2 years in France. 7-unit array planned for Ras Blanchard as part of TIGER project	N/A	Morlais demonstration zone, Anglesey.
Aquantis	Floating turbine	N/A	Single turbine blade on spar attached to a moored vessel. Vessel appears to be fixed in place.	Could attach cameras / active acoustic devices to underside of vessel, or upward looking from seabed.	N/A	Morlais demonstration zone, Anglesey.
Sustainable Marine Energy	PLAT-O, PLAT-I. Floating and midwater tidal turbine.	N/A	Moored vessel, pivoting spar(s) which swing down to deploy turbine blade below (behind vessel. Vessel follows the tide on mooring, so not fixed in place.	Vessel moves, so camera / active acoustics would need to be on board.	N/A	Morlais demonstration zone, Anglesey.
Magallanes renovables	Floating turbine	N/A	Double turbine blades mounted below a moored ship. Vessel appears to be fixed in place (moored at both ends).	Could attach cameras / active acoustic devices to underside of vessel, or upward looking from seabed.	N/A	Morlais demonstration zone, Anglesey.
Cambrian Offshore South West Ltd. (TIGER project)	DeltaStream seabed tidal turbine	N/A	Bottom mounted traditional turbine with blades.	Fixed in place and can be observed by fixed (moored) unit.	2022	Ramsey sound

5. Species around Wales

The species groups within the scope of this review include marine mammals, seabirds, and fish. For determining monitoring requirements and consent conditions, regulators will need to decide, based on EIA, HRA and licence applications, what is reasonable and proportionate (or legally required), for any particular application.

The life history of these species determines the level of risk that tidal stream and tidal range energy devices may cause. Within each of these groups different species can exhibit considerable variation in behaviour, which will affect monitoring requirements and the applicability of different monitoring tools. For that reason, we summarise some key points here.

5.1. Marine Mammals

Around the coast of Wales, the most commonly found species of marine mammals include five cetaceans: Harbour porpoise *Phocoena phocoena*, Bottlenose dolphin *Tursiops truncatus*, Short-beaked common dolphin *Delphinus delphis*, Risso's dolphin *Grampus griseus*, Minke whale *Balaenoptera acutorostrata* and one pinniped species, Grey seal *Halichoerus grypus* (Baines and Evans, 2012). The species most likely to require assessment at wave and tidal stream sites around Wales are thought to be harbour porpoise, bottlenose dolphins and grey seals as they are the most abundant and the only Annex II designated species under the Conservation of Habitats and Species Regulations 2017, which requires the UK to report on their status and protect against activities that would lead to a less than favourable conservation status. In some specific RA common dolphins and Risso's dolphins may be present (Sparling et al., 2015) and Minke whales have been regularly seen in RA including Strumble Head and Ramsay Sound.

Marine mammal presence can be evaluated using visual surveys as they surface regularly to breathe.

From a monitoring perspective, some significant differences are as follows:

- Grey seals regularly haul out which enables them to be surveyed (pup and adult counts), but also allows capture to apply tags, including satellite, GPS, and sensor packages. That approach is not available for cetaceans because of risk to both the animal and researchers during capture.

- Cetaceans vocalise underwater, and their presence and location can therefore be detected using passive acoustic monitoring, although the rate of calls varies between species as some (e.g., harbour porpoise) vocalise almost continuously, while other species such as the baleen whales do not. Passive acoustic monitoring is not applicable to seals.

5.2. Seabirds

Of the seabird species present and breeding in Wales, those more likely to encounter and interact with seabed mounted tidal turbines are deeper diving birds, however, a wide range of birds could encounter surface mounted devices, including those which perform shallow dives or feed on the water's surface.

Species that show a limited use of tidal stream environments (such as gulls *Laridae*, petrels *Procellariidae*) and those that rarely dive to the operating depths of seabed-mounted devices (diving ducks *Anatidae*), are at reduced risk of interacting with tidal stream energy developments. Plunge diving species (Northern gannet *Morus bassanus*, and terns *Sterna sp*.) do not generally travel far horizontally through the water thus limiting their risk of encountering seabed-mounted devices and those deployed at the surface. Plunge diving species rely heavily on visual cues to detect prey from above the water (Capuska et al., 2012) and so they are not as likely to forage and encounter devices placed at the surface or those moored onto fixed features where they are obvious obstacles. Gannets can propel themselves short distances underwater (Capuska et al., 2012); so, there is a scenario where they may encounter a device based closer to the surface during the pursuit phase of a dive where the animal may have reduced visibility or ability to evade obstacles or the pull of the current when underwater. Where turbines are mounted directly underneath the surface structure or vessel, birds are less likely to interact with these directly but could potentially, be passively transported towards the blades during certain phases of a dive.

The species of concern due to their abundance in Welsh resource areas, and therefore those that have a higher likelihood of interacting with a tidal energy device are: auks *Alcidae*, cormorants and shags *Phalacrocoracidae*, shearwaters *Procellariidae*, divers *Gaviidae,* and sea ducks (various families). Specifically, species considered to be at greatest risk are common guillemot *Uria aalge*, razorbill *Alca torda*, Atlantic puffin *Fratercula arctica*, great cormorant *Phalacrocorax carbo*, European shag *Phalacrocorax aristotelis*, Manx shearwater *Puffinus Puffinus*, great-Northern diver *Gavia immer,* red-throated diver *Gavia stellata, and* common scoter *Melanitta nigra.* There may be large implications for small, Welsh breeding populations of black guillemot *Cepphus grylle*, and common eider *Somateria mollissima* (Furness et al., 2012). The aforementioned species are all capable of diving to depths greater than 10 m, with several regularly performing dives greater than 30 m. These species choose to forage in tidal stream environments. This results in an inherently higher likelihood of encountering a sea-bed mounted turbine or a surface-based wave device when foraging in areas of spatial overlap.

Seabirds are a well-researched study system; census data and collation of tracking studies provide unambiguous evidence that describes their marine distribution and degree of 2-D spatial overlap with tidal resource areas. Seabird distributions and general foraging hotspots are commonly evaluated through visual observations or by vessel-based transects. Results of these methods give a consensus about the degree of overlap in space-use. Evaluating actual collision risk for diving bird species remains a core priority for developers and researchers; pioneering the use of sophisticated animal-borne data loggers is one of the ways in which we can begin to build empirical data to help inform Collision Risk Models (CRM) and agent-based models. Local surveys of resource areas to determine relative or absolute abundance of birds present are still required and suitable protocol should be developed for MRE which mirrors that required for offshore wind e.g., 2 years of baseline surveys across all seasons plus further data collection at intervals for years where devices are operational. Few data exist which evidence how birds use the underwater environment during a dive and how foraging in highly tidal environments can influence bird behaviour. Providing insight into how birds select to forage in specific micro-habitats of broadly tidal areas and how they utilise the underwater environment is essential to providing empirical data for the sector to use. More sophisticated monitoring techniques, such as tagging, currently provide the most effective method for visualising underwater behaviour and inferring the potential for interactions to occur between birds and underwater energy devices.

5.3. Fish

The principal fish species of concern are migratory diadromous fish, particularly those protected by the Conservation of Habitats and Species Regulations (2017). While fully marine species may also be impacted and can be a consideration for EIA, these tend to have large population sizes and are often widely exploited by commercial fisheries. In contrast to fully marine species, diadromous populations around Wales may show fidelity to specific river systems or spawning areas, resulting in relatively small populations, or as in the case of European eel, they are considered threatened at current stock levels. These species are also identified as the strategic priority by ORJIP OE (2020) and in a review commissioned by NRW and linked to this study (Clarke et al., 2021a), NRW have identified Atlantic salmon *Salmo salar*, sea trout *Salmo trutta*, allis and twaite shad *Alosa Alosa* and *Alosa fallax fallax*, river and sea lamprey *Petromyzon marinus L.* and *Lampetra fluviatilis*, European eel *Anguilla anguilla* and European smelt/sparling *Osmerus eperlanus* as priorities. The NRW review (Clarke et al., 2021a) looks at life history, and monitoring options for these species in detail, with a second report (Clarke et al 2021b) focussing particularly on the strategic deployment of receiver arrays across Wales, combined with acoustic tagging to identify and quantify distribution of sentinel populations.

Atlantic salmon, sea trout, European eel, river and sea lamprey are widely distributed around Welsh rivers. European smelt/sparling are thought to be limited to North Wales (though they are found elsewhere in the UK) and are only known to spawn in the River Conwy, while twaite shad spawn in the rivers, Severn, Usk, Wye and Tywi, all of which discharge into the Severn Estuary. There are no known spawning populations of Allis shad in Welsh rivers, and only one (in the river Tamar) in the rest of the UK.

Unlike marine mammals and seabirds, fish distribution cannot easily be determined from visual observations at the surface. Evidence describing coastal migration paths and marine distribution of all species around Wales, and hence potential vulnerability to MRE developments, is limited.

Atlantic salmon, sea trout and twaite shad all show high fidelity to river systems, and populations need to be managed by catchment. All three species are likely to migrate through potential RA, both on exit and return to river systems. Both salmonid species are thought to utilise surface waters for the majority of their marine migrations, and hence they are likely to be more vulnerable to near surface devices. However, they do make deep dives on occasion.

Many twaite shad and sea trout survive spawning and migrate back to sea. They also tend to inhabit coastal waters, in contrast to Atlantic salmon which migrate long distances to feeding grounds. As a consequence of both behaviours, they are likely to be exposed repeatedly to MRE impacts. Apart from juvenile shad (too small) all life stages can be tagged with acoustic tags.

European eel is catadromous, spawning in the marine environment (the Sargasso Sea) and are thought to be a single European stock. They migrate through coastal waters as glass eels, entering estuaries and rivers to feed and grow. They migrate back to the Sargasso as Silver eels after many years.

Lamprey spawn and develop in rivers but are not thought to show fidelity to individual systems (Moser et al., 2015). Marine distribution is poorly understood but the limited evidence available suggest that river lamprey may stay closer to their natal river than sea lamprey.

6. Monitoring tools and approaches

There are a range of device types being considered for deployment in Wales. In general, there are:

- Fixed location devices mounted on the bottom/sea floor,
- Floating turbines, mainly operating toward the surface,
- Midwater devices such as the tidal kite operated by Minesto.

Section 8 discusses these MRE devices in further detail. This section focuses on the monitoring equipment currently available or emerging which could be used to monitor devices in Welsh waters.

A number of research organisations are attempting to develop integrated monitoring tools to evaluate MRE impacts. However, these remain experimental rather than COTS tools. To date developers have therefore sought to work with research groups developing such tools or create bespoke monitoring equipment utilising existing known monitoring techniques.

This section identifies the monitoring tools which could be used for both pre- and post-consent monitoring and evaluates the extent to which these tools are applicable in the Welsh environment to address the functional requirements for monitoring. At a high level these comprise of tools for evaluating distribution (geographically and in the water column) and hence the likelihood of encounter with a turbine (literature, visual and catch surveys, tags, eDNA) and near field observations of avoidance and collision (visual and acoustic observations of the device; Passive Acoustic Monitoring, tagged animals).

6.1. Visual survey tools

The first step in determining whether a species is at risk of collision is to determine whether it utilises the development area in question at distinct stages in its life. Visual observations of seabirds and cetaceans, or commercial/research catches of fish can provide evidence of presence, and in certain circumstances potential abundance. Visual surveys can also be useful in validating observations from other monitoring tools, such as active acoustics or passive acoustics. Validation of this type is important in the development of target classification tools and machine learning algorithms.

6.1.1. Marine mammals

Visual observation surveys conducted by marine mammal observers (often referred to as MMO) have been conducted at all tidal energy sites and by all projects to date (ABPmer, 2020). This type of survey can be conducted from a vantage point on shore (land-based), boat-based or using aerial surveys.

Vantage point surveys, particularly land-based surveys where they are practicable, can be relatively cheap to undertake allowing a substantial evidence base to be collected and are especially useful for tidal energy sites that are close to accessible coastline which offers strategic observation points. Most land-based visual surveys consist of visual scans in a predetermined field of view (FOV) area which is site specific. Scans require a minimum of two persons, one observer and one recorder. This method would be able to provide some evidence of far-field avoidance, although limited to surfacing behaviour.

Boat-based surveys are used to collect baseline presence and abundance data and usually require a larger team of observers with up to two primary observers and two secondary observers to maximise sightings. This method provides density data and could be used to assess far-field level avoidance.

The emergence of small Unmanned Aerial Vehicles (UAVs) may provide options for conducting aerial surveys over tidal energy hotspots. UAVs have been used successfully for surveying numbers and sizes of pinnipeds at haul-out sites (Goebel et al., 2015; Seymour et al., 2017) and have been trialled for counting seal pups in the Skerries (Ocean Ecology, 2018). This method could still be used for tidal sites to map positions of surfacing marine mammals (and seabirds) in relation to hydrographic features (e.g., boils, shearlines (Cole *et al., Unpublished))*. Video surveys can then be geo-referenced to give more accurate positions with the tidal site. As surveys of this kind are more cost-effective, numerous surveys could be conducted. UAV surveys usually require just one operator (pilot with commercial licence) and a spotter for safety.

A key constraint on techniques such as active acoustic technologies is classification (species identification) of observed targets. Time stamped visual observations of cetaceans or seals in close proximity to turbines where observations are being undertaken can link species and acoustic tracks, both providing direct data and providing data which can be used to improve acoustic classification techniques.

6.1.2. Seabirds

Vantage point surveys (visual observation), aerial surveys and recently, UAVs, are used to assess presence/absence of birds in tidal resource areas and may provide additional information on micro-habitat space-use. Transect surveys via vessel are frequently used to gather presence/absence data and identify key, broad-scale foraging sites where large numbers of birds are recorded diving (Waggitt et al., 2014).

Aerial surveys can also provide accurate information on the distribution of individuals over large areas (Camphuysen et al., 2004); however, the costs of this technique mean that few surveys tend to be run per season, limiting the ability to monitor changes in space use through time.

Theodolites are instruments originally used for land surveying and have also been used for animal tracking (Piersma et al., 1990; Bailey & Thompson, 2006). This approach to animal tracking allows individuals to be identified. Individuals can be followed, allowing users to reconstruct movement tracks (Bailey & Thompson, 2006). Theodolites are relatively straightforward when it comes to the collection and processing of data (relative to radar data, for instance). They can also provide locations with high accuracy and precision when compared to land-based or seagoing surveys that use grids to allocate observations to geographic areas. Other non-invasive static methods like 3D video tracking can yield similar precision with more temporal resolution than theodolites (positional error of 3D video tracking can be a few centimetres at closer ranges), but these are limited to ranges of up to a few hundred meters (Cavagna, et al., 2008).

The Vector Ornithodolite (VOD) combines a theodolite with a high-grade laser rangefinder enabling highly accurate position fixing which is of precision comparable to GPS. Cole et al. (2019) collected data in Ramsey Sound, Pembrokeshire, UK, where a tidal turbine is currently installed but non-operational (Evans et al., 2015). This allowed examination of the factors affecting the fine-scale space use of seabirds diving in a highly dynamic tidal environment. Hydrodynamic numerical model simulations of current flows in the Sound were used to investigate the conditions that birds select during foraging and whether they exploited certain current characteristics which could otherwise influence their likelihood of occupying the same space as the installed DeltaStream device.

6.1.3. Fish

Although visual surveys are widely used to establish general distribution and areas utilised by seabirds and cetaceans, they have limited value for fish, which are rarely visible from the surface, particularly with the limited underwater visibility found around Wales. The equivalent survey tools for fish typically include direct capture. A more extensive description of capture methods for the diadromous species of interest is provided by Clarke et al., (2021a).

Baseline surveys of both near and far field areas to establish the presence / absence of fish both prior and post implementation of tidal turbine infrastructures may also be undertaken by using non-destructive / non- extractive Baited Remote Underwater Video (BRUV) techniques (Jones, 2020) and combined with clear liquid optical chambers they may be applied to low visibility, dynamic environments associated with renewable developments (Jones et al., 2019).

6.1.4. Visual survey limitations

In all visual surveys, effort is also noted; the amount of time spent surveying is recorded alongside weather conditions, sea state, and for boat surveys - boat course and speed. Pros and cons for visual methods are listed in table 4 from the ABPmer (2020) report, but the main limitations for visual surveys are listed below:

- Animals can normally only be seen at or above the sea surface.
- Visual surveys are restricted to daylight hours and good weather conditions, sea state <3, good visibility, and wind speeds for UAV.
- Labour intensive (boat and vantage point).
- Can be more difficult to spot cetaceans and seals in dynamics areas of the study site.
- Aerial and boat surveys can incur high costs.
- UAV surveys require a UAV operator with commercial licence, and post-survey processing.
- UAV (Unmanned Aerial Vehicle) flights are restricted by battery life (usually ~20mins each, but most users have numerous batteries).

6.1.5. Summary

Visual surveys can help address a range of functional requirements for seabirds and mammals, including FR1, FR2, and FR3. They are a relatively simple method for determining species presence and can directly inform far-field distribution and avoidance behaviour of these species. Data collected using accurate more advanced location techniques may be linked to other datasets such as active acoustic techniques to provide direct data and improve classification techniques.

Dependent on method, surveys can be relatively cheap but are limited to good weather conditions and daylight hours. Visual surveys have been undertaken at many tidal energy sites around Wales by existing MRE developers and baseline data may already exist for some locations.

6.2. Environmental DNA (eDNA)

As animals move through water, they leave tiny traces of their DNA behind. eDNA analyses and molecular techniques can amplify this DNA (or parts of it) in order to identify the species present. This identification can be undertaken using Polymerase Chain Reaction (PCR) followed by Sanger sequencing, metabarcoding or Next Generation Sequencing (NGS).

Both Sanger sequencing and NGS techniques have strengths and weaknesses (Harper et al., 2018; Holman et al., 2019). Both use PCR and qPCR, which is the amplification of genetic material using a primer pair (oligos) specifically designed to identify the target species. The Sanger sequencing approach provides more sensitivity for the target species, and a longer, more specific resulting sequence.

Metabarcoding and NGS amplify specific regions of a gene, giving a full list of species present from the chosen gene region. For example, the fish specific 12S-V5 primers will amplify the 12S variable region 5, and identify several species of fish (Miya et al., 2020). Primers can be chosen to enable us to look at all the species of interest in a single analysis, and they are well covered in existing sequence databases. It can, however, be less sensitive than Sanger sequencing and gives shorter, more variable, reference sequences.

As with most techniques, use of eDNA has both strengths and weaknesses. With the correct sampling strategy, it can be used to determine the presence or absence of target species in a marine area (absence requiring an assumption that it equates to detection thresholds or above), including seasonality of presence and relative abundance (Mynott and Marsh, 2020, Ratcliffe et al., 2021). The collection of data once, for all species around Wales, would provide consistent baseline data for all MRE assessments, which would have wider application for other developments (Annex 5).

6.2.1. Limitations

DNA collected will have been transported by tidal movement, so the technique cannot identify fine scale distribution of species.

To determine absence, rather than presence, a threshold detection level needs to be agreed which constitutes absence for practical purposes.

6.2.2. Summary

eDNA analysis applies to FR1 (presence/absence) only. It is of particular value for fish, where other techniques are limited, though once samples have been collected, it can be applied to any species group. If the samples are properly stored it can provide prior data to identify the species which are important in a particular area, and those which are not present and can therefore be excluded from further assessments.

6.3. Underwater optical cameras

Cameras are important tools used in marine exploration to assess species abundance, diversity, and behaviour (Mallet & Pelletier, 2014). They are a highly repeatable sampling method which can be used over broad temporal (hours to years) and spatial (metres to kilometres) scales. Recent advancements in aspects such as battery life, video quality, underwater housings, cost, and data storage have increased the application of these methods in challenging underwater environments. The cost of camera systems including software, and maintenance have however decreased dramatically over recent years improving the feasibility of such systems to be implemented in underwater monitoring programs (Bicknell et al., 2016; Jones, 2020).

6.3.1. Current equipment and applications

Direct visual or video assessments can provide valuable information for monitoring marine animal presence, abundance, and behaviour as well as collision monitoring for marine animals and turbines. These techniques are often used in tandem with sonar technology for ground truthing (See Section 6.6). Optical cameras may be deployed remotely (battery) or powered by source depending on monitoring targets. Camera visibility ranges from up to 50 m, to less than 10 m depending on turbidity and light level (Jha, 2016). However, due to the dynamic locations where turbine devices have the potential to be deployed in Wales, visibility levels may be reduced. In this instance, literature suggests that recording in black and white may be favourable over colour functionality (Figure 4) and can reduce video quality when filming in low light turbid conditions (Hutchison et al., 2020).

Figure 4. Comparisons of image quality of SR205 colour and monochrome video footage (Hutchison et al., 2020).

Where feasible, the placement of underwater video systems on or near to turbine structures may be beneficial in monitoring the activity of marine animals in the immediate area of a turbine (<30 m) (McConnell et al., 2013). Such systems can potentially confirm physical contact between turbine blades and objects (debris) or marine animal individuals (Jha, 2016). In clear, calm waters marine animals may be readily identified and counted at distances up to 15 m by video systems (Belcher et al., 2002; Langkau et al., 2012). The addition of scale bars to the nacelle and or / turbine blades can also aid this identification (Hutchison et al., 2020). Cameras may also be able to differentiate colliding object properties (density, shape, mass) depending on environmental conditions (Jha, 2016). Tidal devices do not show conformity in design, the mounting configurations for underwater cameras depend on the set up of the marine energy device being monitored in turn dictating the quality of information acquired. This presents different options for camera configurations. For example, a turbine fixed to the seabed can make use of additional platforms to enhance fields of view which would be impractical for floating turbines such as SR2000 or the Minesto Kite. Positioning cameras on additional structures will optimise video coverage and incorporating both wide and narrow angle cameras may also provide a better coverage of the swept areas of rotators (Hutchison et al., 2020).

Preferred mounting configurations of underwater cameras tend to be on the tidal device itself, positioned so the blades are in the field of view. The OpenHydro tidal turbine installed at the European Marine Energy Centre, Scotland utilised Triplex 8 Channel DVR, linked to a Submertec Camera System mounted to the outside of the OpenHydro Ltd platform device. The camera system was mounted approximately 2 m from the face of the turbine allowing continuous recording of the entire 6 m turbine area to monitor ecological interactions around the turbine. The video footage was collected manually after the full trial period each year and transferred to a compatible video computer Programmable Logic Controller (PLC) software system (Hutchison et al., 2020; Aquaterra 2020). Similar deployments of underwater cameras at the back of turbines forward facing on to the blades have also been recorded for the Sabella D10, France. Additionally, tripods positioned under the turbine have also been suggested here with a field of view looking up at the blades.

The MeyGen Tidal Array, Scotland used a similar approach to the positioning of cameras for the monitoring of turbines. Here, three cameras (Seacam Ultra Wide-Angle Monochrome UV) per turbine were mounted on the nacelle just behind the hub and positioned at 120° around the nacelle to capture 360° view of the turbine rotor. The field of view of these cameras were limited to 3 m x 3 m square. The aim of these cameras was to provide evidence of blade conditioning and environmental monitoring. Additionally, two video cameras (progressive scan CMOS) were also initially planned to be mounted on the legs of the turbine support structures (positioned at the base of the turbine), positioned facing upwards with the aim of observing blade conditioning, animal collisions with the turbines, and to supplement other data collected by other techniques (Hutchison et al., 2020, Aquaterra 2020). These cameras used a fisheye lens to cover 180° by 360° (MeyGen, 2016). We were unable to find clarification whether this mounting configuration on the legs of the turbine was utilised during the monitoring programme.

For floating tidal devices such as the Orbital Marine Power SR2000, Vivotek bullets – IP8332 surface cameras and Vivotek domes – FE8174 underwater cameras have been utilised. These cameras are outdoor IP cameras designed for low-light locations. They allow for a 180 – 360° fields of view allowing for coverage of wide-open areas. Here, one camera was positioned towards both blades on leg brace, one under turret and one each on the turbine nacelles, aimed towards the tips of the left and right turbines respectively. Deployments using these cameras on the Orbital Marine Power SR2000 device identified that limited useable footage was collected at night. Biofouling was also present, especially during the summer months, reducing video quality (Hutchison et al., 2020, Aquaterra 2020). It is important to note that with all camera deployments monitoring environmental interactions with tidal turbines, image and video quality varies significantly depending on whether the turbine is active and the time of day with environmental conditions such as weather, season, currents, and suspended sediments potentially reducing visibility. This influences the ability to observe near-field behaviour of marine animals with turbine devices (Hutchison et al., 2020).

Numerous open source and proprietary software types including packages which come as standard with equipment and post-processing software exist for analysing underwater imagery and video. Such software is constantly evolving and incorporating new analysis techniques. An example of this is the open access VIAME application which allows for do-it-yourself artificial intelligence including object detection, object tracking, image/video annotation, image/video search, image mosaicking, stereo measurement, rapid model generation, and tools for the evaluation of different algorithms.

6.3.2. Stereo cameras

Stereo–optical cameras (both baited and un-baited) have successfully been used to accurately measure marine animals (specifically fish) giving an additional confidence for species identification in marine monitoring programmes. For example, Griffin et al. (2016) have previously implemented such systems around wind farm infrastructure to monitor fish.

Un-baited stereo camera systems have also been successfully applied to the post-installation environmental monitoring of interactions of marine mammals with hydrokinetic turbines with such systems performing well in high energy areas (Joslin et al., 2012; 2014).

6.3.3. Optical camera limitations

Several limitations exist when using optical cameras for marine animal monitoring around tidal stream developments, especially in turbid waters such as those found in certain parts of Wales (e.g., Bristol Channel). The effective range and accuracy of optical cameras underwater is very site specific. Limitations include:

Turbidity / decreased underwater visibility

Optical camera methods are heavily reliant on good levels of underwater visibility. Such visibility and visible range are reduced in high energy areas subject to elevated levels of turbidity through suspended particulate matter (SPM) such as those associated with renewable developments. This in turn reduces their reliability for accurate species detection and identification when characterising features for individuals are not visible (Jones et al., 2019). Furthermore, this visibility reduces the distance in which optical cameras can be deployed from the turbine to visualise any direct collisions or blade conditioning. Turbidity levels can be affected by season (algal blooms), tides, water currents, depth, and sediment composition, all of which will differ by location and should be considered when choosing camera monitoring techniques.

Lighting

Digital camera methods are limited to daytime activity monitoring and certain depths where the water column is naturally illuminated. The addition of artificial lighting to monitoring cameras may increase useability during night-time/deep deployments but may have adverse effect on marine animals by influencing behavioural changes (Joslin et al., 2014) and even attracting individuals closer to turbine infrastructure if within close proximity (Inger et al., 2009). Alternatives in this instance include monochrome cameras which are suited to working in low-light conditions and accrue smaller data files than colour video (Hasselman et al., 2020). To compensate this, subsea cameras have adapted emerging technologies and have demonstrated low light image capture. Multi spectral imaging provides depth perception and enhanced contrast for example, blue and green illumination/filtering. Ultraviolet wavelengths have been used to detect fluorescent tracers and other UV luminous materials. The high absorption coefficient of infrared wavelengths in water limits the utility to close (a few cm distance) thermography applications (Jha, 2016). Monitoring of the MeyGen Tidal Array for example used three Seacam Ultra-Wide-Angle Monochrome UV cameras to monitor presence/absence of marine animals in low light/turbid conditions (Hutchison et al., 2020). Monochrome cameras can provide high resolution images in ambient light conditions without the need for artificial light.

Field of view

The field of view of a digital camera when deployed in a fixed position underwater limits these methods such that they can only be used for detections of animals observed rather than counts of individuals (Paiva et al., 2015). The spatial distance/range of a digital camera is limited even in perfect underwater visibility conditions meaning they are unable to detect animals in wider areas of turbine installations when underwater. Most configurations of cameras previously used for device deployments are in a fixed position looking at the turbine blades. Additionally, the camera view can be obscured at times by the turbine blades or the field of view may not cover the entire rotor area, meaning not all encounters may be captured (ABPmer, 2020). When deployed underwater in a fixed position, they are unable to track and map the movement of marine animals. Mitigation for this may be the inclusion of acoustic tools with real time target assessments to allow control of camera tracking. In some instances, cameras can be mounted in a 120 ° configuration around the nacelle to capture a 360 ° view of the turbine rotator.

Data storage requirements

One of the main challenges associated with the analysis of video and imagery data is the ability to save, store and access it in an efficient manner. High quality video (High Definition) data has burdensome storage requirements and very much depends on the camera system and settings being used. Data that has previously been obtained using Seacam Ultra-Wide-Angle Monochrome UV cameras during tidal device monitoring suggested that each turbine generated approximately 2 GB of data in a 24- hour period (approximately 60 GB / per month / per turbine). Data storage requirements will depend on the camera system being used and the quality of the data being collected, higher quality/resolution means more storage would be required. Similarly, to active acoustics, fibre optic cables to shore are a preferred option for data transferal. The use of a Network Video Recorder (NVR) and satellite transmission may however allow for substantial amounts of data to be transferred and stored for comprehensive study as and when required (Hutchison et al., 2020). Proximity sensors in the form of active acoustics may be used to reduce data volume. They can be used to trigger camera devices from standby/data rewrite mode to record and store mode when marine animals have been detected near turbine structures (Jha, 2016). Triggering systems have previously been successfully implemented by Nova Innovation in the Shetland Tidal Array. Implementing such systems must be considered to reduce long-term data storage costs.

Power and corrosion

Powering underwater cameras for long term monitoring is challenging. Localised battery banks powered by the turbine itself can provide an effective method for powering equipment to avoid possible issues and costs by connecting to a power supply external to the turbine. Faulty connections and corrosion can hinder video monitoring efforts. Power supply solutions should be designed to withstand the environmental conditions within which they are to be deployed (Hutchison et al., 2020). Ideally these issues should be integrated into the preliminary stages of turbine design.

6.3.4. Summary

Optical cameras are valuable tools for looking at near field interactions (FR3), and in clear water during daylight hours are probably the method of choice for this requirement. As with visual surveys they can be used to identify species linked to acoustic or other tracking data, providing validation data for target classification.

Around Wales, underwater visibility is poor – in many areas limited to a few metres in good conditions. This limits the value of these techniques; inclusion of inexpensive equipment alongside other techniques would be recommended to take advantage of good conditions but would only consider wider use if local surveys demonstrated that adequate visibility could be expected.

6.4. UAV and remotely operated vehicles (ROV)

For a wider field of view, Unmanned Aerial Vehicles (UAVs) equipped with digital cameras may be a useful tool, especially for marine mammal monitoring (Mellor & Maher, 2008) and for baseline environmental assessments. Such baseline assessments may be used to determine the species present in an area and inform subsequent monitoring methods and assess whether a turbine would give cause for concern at population level. UAVs provide the ability to repeatedly collect high-resolution aerial imagery of animals at or close to the surface over large areas using High Definition (HD) camera technology in a manner that is unobtrusive to animals when flown at heights approximately 120 m above the sea surface (Aniceto et al., 2018) and are particularly advantageous when performing studies focused on animal abundance and distribution (Aniceto et al., 2018; Bröker et al., 2019). It is not therefore surprising that most tidal energy projects have undertaken some form of visual monitoring observation such as UAVs (ABPmer, 2020). Such methods can detect and identify the presence of some species of concern around the locality of a turbine (>60 m), however, observing direct collisions with tidal stream devices or avoidance behaviour of marine mammals through UAV methods is limited while individuals are below the surface and battery power is also limited to 30 mins to 1 hour for most UAVs. Subsea drones and remotely operated underwater vehicles (ROVs) may be used as alternatives to visualise marine animals underwater. Such systems are becoming more readily available at lower cost and can be deployed from a range of vessels including rigid-hulled inflatable boats (RHIB) (Ludvigsen & Sørensen, 2016; Verfuss et al., 2019). Unmanned subsea vehicles may therefore be better placed monitoring the wider area of tidal devices (>60 m).

6.4.1. Limitations

Many ROV may struggle with the tidal currents around MRE sites. There are risks associated with deploying unmanned, 'unattached' devices close to subsea infrastructure including damage to the tidal turbine devices themselves through collision with blades.

The use of aerial digital cameras in UAV (Unmanned Aerial Vehicles) surveys for marine mammal monitoring in the wider area of a turbine is restricted by environmental conditions including weather and sea state. Flights of UAVs must be undertaken in favourable weather parameters where detectability of marine mammals is high whilst adhering to regulatory restrictions. Such parameters include cloud cover, surface glare, sea state and time of day. Surveys are usually conducted in sea-state conditions of Beaufort < 3 (Colefax et al., 2018). For example, most quadcopter drones have limits of wind speeds of 10 m/s. Such limitations are usually written into commercial drone operator manuals which are approved by the Civil Aviation Authority (JNCC, 2019). Most permissions granted to organisations from the Civil Aviation Authority impose restrictions whereby the drone must be in visual line of sight (VLOS) at all times and less than 500 m distance from the pilot (unless special extended visual line of site permissions is obtained).

6.4.2. Summary

UAV and ROV can be valuable in wide area surveys and potentially in spotting marine mammals to link to species classification in fine scale studies. Care needs to be taken with regulatory and practical issues.

6.5. Passive acoustic monitoring (PAM)

Passive acoustic monitoring is an invaluable tool for monitoring echolocating cetaceans *in situ*. Most cetaceans found in Welsh waters routinely vocalise while underwater, and consequently can be detected by passive monitoring equipment while they are vocalising. This can allow detection of presence or absence of cetaceans in an area, as well as identification of the species concerned. It can be cost-effective, limits influence from observer presence (especially boat-based surveys) and allows for continuous data collection throughout the diel cycle and in adverse weather conditions that would limit observers (Simon et al., 2010).

One of the main data gaps in collision risk modelling for marine mammals is how they use high energy tidal sites, within the water column, including numbers of animals and depth distribution. In addition to detection and identification, arrays of hydrophones can be used to determine cetacean position in the water column, using differences in the time of vocalisation arrival. With the correct configuration of hydrophones, and precise time synchronisation of equipment, it is possible to spatially locate vocalising animals (Macaulay et al., 2015b). This requires four or more well spread and time synchronised hydrophones or hydrophone clusters detecting the same vocalisation to enable the position of the animal to be calculated.

Odontocetes (toothed whales, including harbour porpoise, common, Risso's and bottlenose dolphins) use echolocation for feeding as well as communication and orientation. Harbour porpoise are known to vocalise frequently, with distinctive high frequency narrow band, whereas dolphins vocalise less frequently with shorter, more variable clicks at lower frequencies (Au and Hastings, 2008). Mysticetes (baleen whales, such as minke whales) emit much lower frequency noises (<1 kHz) which can be easily masked by environmental noises such as sediment movement (Hasselman et al., 2020). These whales do not use echolocation but do use song for communication. High frequency clicks from porpoise are distinctive, yet are quickly attenuated (Macaulay et al., 2017) in comparison to lower frequencies which means dolphin (and potentially minke) can be detected from further away. The ability to detect and track Odontocetes, particularly porpoise, is far more feasible using PAM than for Mysticetes like Minke that communicate infrequently. Although long-term PAM arrays have been used for detecting seasonal and diel patterns of minke whales in the North Sea (Risch, et al., 2019).

Using these techniques, SMRU have successfully monitored porpoise movements around functioning tidal devices, including Delta Stream, Ramsey Sound (Malinka et al., 2018) and in Pentland Firth, Scotland as part of the MeyGen project, using hydrophone clusters (Gillespie et al., 2020).

PAM can also be used to measure noise caused by underwater MRE devices which can cause disturbance to marine mammals affecting navigation, predation, communication, and life cycles (Hasselman et al., 2020). Depending on the monitoring device and signal filtering or triggers used, recording device noise could require an additional hydrophone deployment.

6.5.1. Equipment

Details of the PAM technologies that have been used for MRE environmental surveys around the World are listed in the State of Science report, including deployment locations, equipment configurations employed, acoustic measurement type, and related references (Hasselman et al., 2020; copy attached in Annex 6). In general, techniques employed consist of hydrophones which are deployed on fixed or mobile platforms. Fixed deployments include bottom mounted, moored, or turbine mounted arrangements. Mobile deployments include drifting (boat or buoy) or towed (boat). Static acoustic monitoring devices (SAM) are useful for determining temporal patterns, whereas towed arrays provide spatial coverage (Wilson et al., 2014). Hydrophones are typically deployed in singular, paired, or clustered configurations, with clusters and arrays used for fine scale studies where detailed location data are required (Figure 5).

Figure 5. Examples of hydrophone equipment, C-POD (left), SoundTrap (middle, from Copping et al., 2020) and custom-built hydrophone cluster (right, photo taken from Hastie et al., 2018).

There are several types of PAM equipment that are commonly used, but the main types consist of conventional hydrophone units that record raw sound data or specialised click detectors (C-PODs) which have integrated hydrophone and data-processing units which undertake initial processing of the data in real time. This allows the data stored by the device to be summary ‘click train’ data, (Hasselman et al., 2020), reducing data storage requirements and allowing extended deployments. Devices can be static, attached directly to a device or on a fixed mooring. They can also be actively towed from a boat or drifted on tides and currents.

T-PODS, C-PODS and F-PODS

C-PODs are self-contained omni-directional static acoustic click detectors comprising a hydrophone, filter, and digital memory (Figure 5). The first version was the T-POD and a newer version has been recently developed, the F-POD (which has improved train detection and species classification; N. Tregenza, Chelonia, pers. Comm., 2020), but they are all the same type of device. These devices detect vocalisations between the frequencies of 20-160 kHz (Dähne et al., 2013; Robbins et al., 2016). They process data *in situ*, recording the processed data rather than raw sound files, which greatly extends the life of individual remote deployments by reducing data storage needs (devices can be deployed for ca. 4 months at a time before battery replacement and data download is required). They can be deployed on relatively simple, low-cost moorings, drifted, boat or equipment mounted and are relatively inexpensive.

Regular baseline signals are also desirable to enable assessment and correction of variations in efficiency, due, for example to background noise. This may be particularly important for studies which seek to correlate cetacean availability with tidal state, or where noise varies significantly across a study area.

C-PODS are especially useful for identifying porpoises as they vocalise frequently with distinctive high frequency narrow band clicks. Other dolphin species echolocate at a wider range of frequencies and can also be detected, however as they do not vocalise all the time detection rates are often much lower than that of porpoises (Nuuttila et al., 2013; Philpott et al., 2017). C-PODs have been extensively used for monitoring porpoise and dolphin presence, with numerous studies being undertaken for the offshore windfarm industry, looking at differences before, during and after installation (Brandt et al., 2011; Carstensen et al., 2006; Dähne et al., 2013b; Scheidat et al., 2011). They are particularly effective in determining tidal and diurnal patterns of porpoises and some other cetacean species (Gordon et al., 2011).

In Nova Scotia, the Fundy Ocean Research Centre for Energy (FORCE) carry out monitoring of porpoises outside of the FORCE test site, in the Bay of Fundy, using PAM. The monitoring of one open hydro tidal turbine device (Cape Sharp Tidal Venture), found that porpoises were not excluded from the mid-field area during installation and operation of the device, although fewer detections were recorded on the C-PODs closest to the device (~200m) suggesting localised avoidance or acoustic deterrence effects of the turbine when operational (Sparling et al., 2020; Tollit et al., 2019). Porpoise presence was found to return to baseline pre-installation levels when the device was removed (Tollit et al., 2019).

Multiple drifting C-PODs have also been used in tidal stream areas with reportedly similar distribution results as more traditional visual and acoustic boat-based surveys (Wilson et al., 2014). This method provides a relatively inexpensive rapid tool for measuring harbour porpoise occurrence and habitat-use within a tidal-stream area and reduces the level of noise from water flow over the hydrophone.

Conventional hydrophones

Conventional hydrophones such as the High-tech HTI-99-UHF can be cabled for live data transfer or combined with recording units and deployed in standalone autonomous units such as the commercially available SoundTrap (Ocean Instruments NZ, ST300 HF) and 'Porpoise' single-channel hydrophone (RS Aqua). This type of hydrophone is designed to record at high sampling rates and substantial amounts of data storage capacity are needed to record cetacean vocalisations (Hasselman et al., 2020). The data can be used for picking up background noise and cetacean vocalisations over a wide range.

For autonomous units such as SoundTraps, the amount of data collected, and data storage requirements are problematic and restrict deployment lengths to days with continuous recording. This can be extended by programming the device to sample intermittently e.g., 10 minutes in every hour. This extends deployments to months but runs the risk of missing infrequent or rare events. There is also the option of increasing deployments using additional external battery packs which can extend continuous recording to 70 days for SoundTrap and 193 days for 'Porpoise' hydrophone.

Hydrophone arrays

Locational studies require hydrophone arrays. Most hydrophone arrays are bespoke custom-built units and are not commercially available.

At the MeyGen site, twelve hydrophones (divided into three clusters of 4) were integrated into an Atlantis AR1500 turbine before it was deployed as part of an array with three other turbines. Calibration of this study showed that the system could accurately locate sounds to 2 m away within 20 m of the turbine, although this accuracy decreased beyond a distance of 35 m (Gillespie et al., 2020). The system was deployed over 2 years resulting with 451 actual days of data collection. A recent presentation of the data shows out of 1516 porpoise encounters, several animals passed close to the turbine whilst it was moving, but only one animal passed through the rotor disk, but the rotors were stationary at the time (Gillespie & Johnson, 2020). Additional data is still to come from the MeyGen project with more systems being deployed this year, however initial findings suggest porpoise avoidance at medium (tens meters) and near-scale (meters) distances to the turbine rotors (Sparling et al., 2020).

Minesto, working with Bangor University (BU) have also deployed bespoke hydrophone clusters to look at cetacean movements around their tidal kite. As the kite occupies different areas during ebb and flood tides, two clusters of 4 hydrophones were required, one to provide data in each area. Initial studies, combined with SoundTrap data, were successful in identifying cetacean presence and tidal availability, but tracking was compromised by equipment failure (water ingress and firmware faults). Minesto plan to redeploy the equipment following repairs (Gemma Veneruso, Bangor University and Minesto, pers comm).

Tidal Energy Limited also deployed hydrophone clusters on the DeltaStream tidal stream device as part of a wider monitoring strategy, including both PAM and active acoustics linked to an Acoustic Doppler Current Profiler (ADCP) to record current velocity. These comprised 4 clusters of 3 hydrophones, mounted on the device structure. Unfortunately, a number of hydrophones in the clusters were damaged during deployment, leaving 5 fully operational and 2 partially operational, limiting the effectiveness of position fixing. Tracks obtained, predominantly of porpoise but also dolphins, inferred a level of detection and response to the device (Malinka et al., 2018).

Other studies have used buoys attached with vertical hydrophone arrays that are designed to drift through tidal rapids (Gordon et al., 2014; Macaulay et al., 2015; 2017). A unit was developed by Macaulay et al. (2015a) called the PLABuoy (porpoise location array buoy) which was made up of an attached vertical hydrophone array (35-40 m, 6-8 hydrophones) to provide porpoise (and dolphin) depth distributions and movements along with a hydrophone cluster for calculating headings. The project also developed open-source software and user guide to provide a cost-effective and relatively user-friendly method for the MRE sector. The developers are refining the PLABuoy with a new system being trialled for towing two or more 3D clusters in streamlined housings and deploying such equipment with orientation sensors on moorings to improve outcomes (J. Gordon, SMRU, pers comm., 2021).

Although C-PODS/F-PODS and SoundTraps are typically used for detecting presence / absence and relative abundance in an area, deployed in closely spaced clusters they could also be used for locational studies; such studies would also require a regular baseline signal from a known point to enable precise clock synchronisation. Clustered groups are necessary because cetacean vocalisations are not omnidirectional and are emitted as a relatively narrow angle beam or cone of sound. We are not aware of trials using standalone COTS devices in this way as yet but in principle they could provide a lower cost alternative to some of the bespoke solutions currently being trialled.

6.5.2. PAM limitations

PAM is limited to cetacean species that vocalise underwater (i.e., not seals, seabirds or fish which do not vocalise).

Practical limitations are listed below.

Ambient noise

It is important there is an understanding of background noise levels at MRE development sites so that changes caused by any MRE device can be detected. Ambient noise tends to be higher (sound pressure level, dB) at high tidal energy areas and at high tidal velocities which has implications for the interpretation of PAM data. Masking of vocalising cetaceans could result in an underestimation of cetacean presence at highest flow rates, potentially giving a false perception of habitat use. This is especially so for dolphin species that use broadband signals, which can be difficult to discriminate due to overlap with background noises caused by flow, turbine operation and boat noise (Gillespie, et al., 2020). Noise from tidal flow past the hydrophone is reduced with the use of floating / drifting PAM devices such as buoys or drogues, instead of mounted or moored hydrophones (Sparling et al., 2020).

Species identification and directionality

Harbour porpoises use distinctive narrow-band, high-frequency echolocation that can be easily identified in hydrophone data (conventional and C-POD). However, dolphin species that use broadband signals, including Risso’s, bottlenose and common dolphins, show significant overlap in acoustic characteristics making it more difficult to differentiate species in C-PODs and conventional hydrophones (Villadsgaard et al., 2007; Robbins et al., 2016). There are still some species-specific parameters that can be used to improve identification, especially for Risso’s dolphins, although some level of expertise would be required (Robbins et al., 2016). Marine mammal vocalisation parameters (signal type, frequency, source type etc.) have been consolidated in Todd et al., (2015) a handbook for marine mammal passive acoustic monitoring. Vocalisation is also directional, requiring careful design of hydrophone clusters if locational tracking is the objective.

Deployment

The challenging conditions associated with high tidal energy sites means that monitoring work is often limited. Moorings for static acoustic equipment need to be heavily weighted and cannot be safely deployed in the areas with the highest current speeds. For example, C-PODs will only record when the hydrophone end is upright in the water column. Detections are compromised when the device is not fully vertical and will stop recording in a horizontal position. If tidal flow is strong enough to deflect the hydrophones towards the substrate, there is also the risk of damage to equipment, compromised data collection and possible loss. This means that PAM equipment is usually moored at a distance from the highest flow rates which will compromise detections at a fine scale. This can be overcome with direct integration of hydrophones onto tidal devices, such as at MeyGen, or use in integrated or purpose-built platforms but this requires significant preparation.

Data storage and processing

Data storage and processing can be challenging for passive acoustic monitoring, especially for conventional hydrophones if they are recording continuously. Although more manageable than active acoustic and video data, hydrophone arrays of ~8 channels (e.g., 8 hydrophone units in 2 x clusters), then up to 8 TB of data can be recorded per day (Sparling et al., 2020). Acoustic data can be compressed, to ease handling (e.g., use of lossless compression in Gillespie et al., 2020) which can allow for increased recording duration (Johnson et al., 2013). Nonetheless, good data management plans are necessary to have in place before the start of any data collection (G. Veneruso, Bangor University pers comm, 2021).

Commercially available autonomous hydrophones vary in storage limits. SoundTraps can store 256GB (Gigabytes) data (compact and 4-channel version) or 2TB (Terabytes) (long-term recorder). The ‘Porpoise’ single channel hydrophone can store 4TB data. This would mean data downloads would be needed every 1-4 days if hydrophones are set to record continuously, based on deployments around Minesto, although this will vary with instrument type. Real time acoustic data from cabled hydrophones (such as towed hydrophone, or MeyGen integrated system) can be processed with open-source software such as PAMGuard (Gillespie et al., 2008), on an onboard computer, to classify and locate signals.

6.5.3. Summary

In summary cluster/array deployments of PAM devices can be used for broad scale studies of cetacean presence and distribution and have been used to gain near field/fine scale data on cetacean movements around turbines. Currently the technology is still developing, and most studies are research led rather than based on commercial off the shelf products. For fine scale tracking array design is critical, and analysis is complex requiring specialist expertise.

6.6. Active acoustic technology

Active acoustic technology is a robust method for monitoring marine life as it can detect and accurately localise targets in the water column. These methods produce pulses of sound electronically using a sonar projector and then monitor for echoes of these pulses as they reflect off objects using one or more hydrophones (Mcconnell et al., 2013). Such technology (e.g., sonar, echosounders, split and multibeam devices) provides a high-resolution (in both time and space) measure of biological (zooplankton and fish abundance and distribution) and physical oceanographic processes (internal waves, micro-turbulence, and frontal systems) through time series of acoustic backscatter measurements (Lavery et al., 2010, Howe et al., 2019). Active acoustics have been previously used in fisheries research to assess biomass, abundances, spatial and temporal distributions, size distributions and population structure. They may also be used to study behaviours such as migration, spawning, feeding, and schooling.

There are a large number of commercially available active sonar systems with one review previously collating an inventory detailing over 200 systems from 39 sonar manufacturers including Sound Metrics, Kongsberg, Tritech, Valeport, Qinetiq, Reson, BioSonics, Simrad, Si-TEX. Of these 200 systems, 24 incorporated automated target detection and tracking software including the BioSonics DT- X and Tritech Gemini systems; however, most of these were designed for vessel or port security rather than for marine wildlife tracking (McConnell et al., 2013).

6.6.1. Current and emerging active acoustic techniques

Active acoustic techniques are designed for a wide range of uses including mapping, underwater navigation, fisheries research, and seabed profiling (Griffin et al., 2020).

In low visibility environments such as those present around Wales (especially the Bristol Channel), active acoustic systems such as echosounders or multibeam sonars, are not limited by light level or visibility because the image is produced by reflected sound, not reflected light. As such, these systems are not affected by ambient suspended particulate matter levels (Belcher & Lynn, 2000). Active acoustics such as acoustic cameras were initially adapted for fish enumeration or identification under conditions of low visibility such as poor lighting or high turbidity (Belcher & Lynn, 2000; Kim et al., 2005; Moursund et al., 2003).

Fundamental transmission frequencies typically range from 12 to 3,000 kHz (McConnell et al., 2013). Such systems include high frequency multibeam sonars or “acoustic cameras”, which are relatively innovative technology, formerly used for surveillance and inspection of underwater structures in the marine environment (Belcher et al., 2002). As acoustic systems enable relatively non-intrusive surveys of marine environments, they are being used increasingly to study marine animal populations as they do not modify their natural behaviour. Animals with strong hearing abilities such as marine mammals can, however, alter their behaviour in response to sonar, in which case sonar systems with frequencies outside of their hearing range are needed.

To be able to measure the behaviour of individuals including marine mammals and fish around tidal energy devices, a sonar system must meet essential specifications including:

- Appropriate spatial coverage (both horizontally and vertically); this effectively determines the volume of water that can be monitored around the turbine.
- Sufficient temporal resolution (ping rate), angular and range resolution to allow target individuals (fish or mammals) to be effectively detected, classified, and tracked.
- No interference with the behaviour of target and non-target species.

These active acoustic systems have previously been implemented in fish, seabird and marine mammal behaviour studies assessing interactions with tidal turbines as well as for the automatic classification of biological targets in general (Williamson et al., 2017). Active acoustic systems such as multibeam have observational ranges of tens to hundreds of meters depending on the frequency (Cotter & Polagye, 2020) and the ability to track individuals (Melvin & Cochrane, 2014). This allows for these techniques to be used for monitoring the activity of individuals in the immediate area of the turbine (<30 m) as well as the wider area (>60 m).

Active acoustic systems have the potential to confirm physical contact between turbine blades and any objects or marine mammal individuals, with some lower frequency systems (< 1 kHz) providing a theoretical range up to 120 m (though practically much less – up to 50 m for seals, SMRU pers comm.) and higher frequency imaging sonars providing a higher resolution at a range of 1 m – 5 m (Jha, 2016). Such systems may be deployed in dynamic, low visibility environments associated with tidal stream developments to detect and identify the presence of species of concern around the locality of turbines (>60 m). In terms of monitoring infrastructure post collision, imaging sonar used at a high frequency may also be able to determine location of contact or collision with turbine blades.

6.6.2 Single beam and split beam echosounders

Single beam echo sounders, which have evolved from analogue devices, through to single frequency, multi frequency wide band and high frequency broadband interactions have long been the go-to method for understanding the environment below the sea's surface. These devices can allow for detection of targets in the water column and classify targets through measurement of responses to increasingly high resolution and ranged sound spectra, in some cases down to species level (Korneliussen et al., 2016). Split beam echosounders can further use differences in ping return times to separate points on the transponder face to pinpoint the location of a target within the beam's signal. Development of these tools has been driven by the fishing industry to target the most profitable fish shoals, and they can be used to identify shoals of some commercial species. The Simrad/Kongsberg group lead most development in this field with the majority of research in recent decades being based around their ES and EK 60 and 80 deployment packages (ES and EK referring to echosounder model) (Sakinan & Berges, 2020).

Although these technologies are useful in fisheries for determination of shoal size, individual fish size within the shoal and species classification, they come with some disadvantages. Of primary concern for monitoring of MRE sites is that, as single beam instruments, their viewing angle is either limited to approximately 7° when focused or a higher angle low resolution beam of up to 120° (Williamson et al., 2017). This means that as a method for monitoring a large area for identification of targets they are of limited use on their own (Williamson et al., 2017), though they add significant value when combined with other tools. In common with other methods which can be used for identification, they also require large quantities of training data to allow classification, which need to take into account variables such as species, size, orientation, speed, ambient conditions, and variations in calibrations (Renfree et al., 2020). As a result of this, and due to the large rate of data production, processing is also a bottle neck for real time monitoring of sites.

There are systems being developed that encompass a number of sonar heads into a single package. Biosonics are developing an omni-directional long-range target detection and classification system which consists of 48 sonar heads which give 360° coverage for target detection. A secondary sonar, the directed classifier, is then automatically aimed at the detected target to track its position in three dimensions and gather higher-resolution data on the density, size, and rate of movement. This is currently under development and being trialled at the Wave Energy Test Site (WETS) in Hawaii.

6.6.3. Multi beam sonars and acoustic cameras

Fish are small targets, and fishery scientists have principally used the Sound Metrics Corp. DIDSON dual-frequency identification sonar (Holmes et al., 2006; Handegard & Williams, 2008; Boswell et al., 2008; Burwen et al., 2010; Doehring et al. 2011; Martignac et al., 2015) especially for identifying and counting migratory fish in rivers. DIDSON allows monitoring at several frequencies, the highest of which is 1.8 MHz which produces high image quality with a 29° field of view. The maximum distance for this frequency is about 12 m. This distance can be increased to 30 m with a lower frequency of 1.1 MHz (Moursund et al., 2003). More recently, the Sound Metric Corp Adaptive Resolution Imaging Sonar 'ARIS' has been improved to operate at 1.8 and 3.0 MHz, the latter providing higher quality imagery at a range of 5 m. This camera has been applied to freshwater and coastal fish monitoring including the validation of fish length measurements (Cook et al., 2019) out to approximately 5-20 m when using the appropriate ARIS SCOPE software and settings. Identifying features such as body shape, size, caudal, pectoral, and dorsal fins may be visible on the sonar imagery depending on the frequency being operated at (Jones, 2020). Behavioural characteristics such as locomotion may also aid identification. Although this camera has been used extensively in freshwater environments, as it stands, this system may be susceptible to marine pressures such as biofouling and corrosion during long-term marine deployments: further research and testing is required to assess its resilience in these environments.

An alternative to ARIS which has been previously used in marine monitoring, including around tidal turbines, is the lower resolution Tritech Gemini imaging sonar which operates at a frequency of 720 kHz for long range target detection (theoretical range 0.2 m to 120 m) and 1200 kHz for close range identification (0.1 m – 50 m). Discussions with the manufacturer suggested that a distance of 40-50 m can be used for detection of marine mammals when operating at 720 kHz, which is consistent with advice from SMRU (above) for seals. Although this is a lower frequency range compared to ARIS, the Tritech Gemini has been the favoured device in integrated multi device solutions, due to its compatibility with other devices and software, its potential to be included in a ‘triggering system’ to avoid recording unnecessary data and cost. It also has a proven resilience to longer term marine deployments and has been adapted for use with protective titanium underwater camera housings. The SeaGen Project in Strangford Lough also deployed a Tritech Gemini sonar system directly on to the tidal turbine using a mounting plate secured to the centre of the crossbeam of the turbine, electrically isolated from the turbine using rubber matting between the head and the mounting plate. The depth of the transducer when the crossbeam was lowered was 11.5 m below MLWS (Mean Low Water Spring) and was close to the middle of the water column. Data transmission from the sonar heads was incorporated into custom built cables within the turbines existing systems cabling. The sonar provided 120 ° horizontal coverage x 20 ° vertical coverage in front of the turbine providing full water column coverage at 68 m from the turbine (Hastie 2013).

There are also 3D multibeam systems, such as the CodaOctopus Echoscope and Echoscope PIPE. The Echoscope uses 375/630 kHz frequencies and produces 128 x 128 beams (16,384 beams total), like having 128 multibeam sonars in one briefcase (Figure 6). This system has been primarily used for underwater construction, cable laying, ROV and diver tracking and monitoring, but has the potential to be used for monitoring animal interactions with tidal stream energy devices.

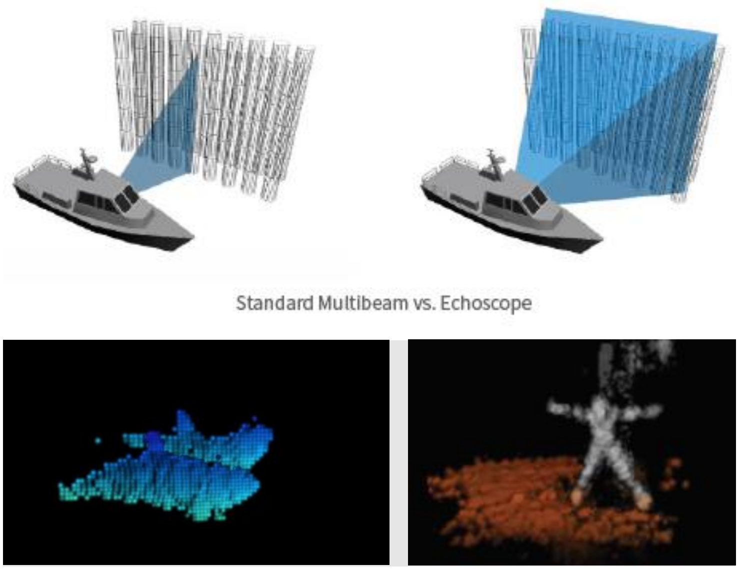

Figure 6. Comparison of standard multibeam coverage versus the Coda Octopus Echoscope coverage (top image), examples of Echoscope imagery (bottom images), taken from Coda Octopus.

The Echoscope PIPE is interesting in this application as it provides the possibility to look at selected data in the whole volume and to operate the sonar in a sequence such as:

- 1st ping: 90 by 44 ° view at 240kHz – wide angle low range (and lower resolution) to cover the whole installation.
- 2nd ping: 50 by 50 ° limited to cover the area of maybe 10 metres in front of the installation to see the marine life approaching the installation.

- 3rd ping: 24 by 24 ° limited to a cover the area right in front of the installation to see marine life going into the turbine.
- 4th ping: 24 by 24 ° limited to cover an area right behind the turbine.
- And then the sequence starts over.

The imagery can then be displayed in a consolidated way or separately for each element of the sequence. The PIPE sonars can operate at up to 40 Hz frame rate so in this example each element of the sequence would run at up to 10 Hz which should be enough to get good quality imagery. The Echoscope and Echoscope PIPE are expensive when compared with most other types of multibeam but there is scope for this system to provide a high degree of coverage if directed looking at a tidal stream energy device. Operational frequency would also need careful consideration to avoid effects on species such as marine mammals.

Multi beam systems can also be applied to other marine animal groups including marine mammals and seabirds. For example, Staines et al. (2020) present findings which trial the combined use of a wide-angle single beam echosounder with an imaging sonar camera deployed from vessels within tidal turbine project sites. Analysis suggested that marine mammals were visible on the camera when operating at a high frequency (1.8 MHz) with a range of 2 m to 12 m below the surface. Species identification of marine mammals is also possible with studies concluding that size, shape, and swimming behaviour for species such as harbour seal *Phoca vitulina*, grey seal *Halichoerus grypus,* and orca *Orcinus orca,* can be identified. Features such as flukes, dorsal fins and body shape were visible on the footage (Francisco & Sundberg, 2019).

6.6.4 Active acoustic limitations

Although presented here as a suite of methods for the monitoring of MRE sites, the core premise of active acoustics devices is broadly similar and as such there is a commonality to the issues and limitations that these instruments encounter:

Interference with the target animal

The Hastie (2013) review tested active sonar solutions from the following manufacturers: BioSonics, Tritech and Codaoctopus. Results suggested that porpoises exhibited relatively subtle responses to the Tritech Gemini system whilst seals exhibited overt responses to the BioSonics DT-X system. Seals and harbour porpoises were also predicted to be able to hear the signals of the Tritech Gemini and BioSonics DT-X at ranges of approximately 60 and 4,000m, respectively. These results suggest that marine animals may react differently to different devices, something which should be considered when creating monitoring programmes. BioSonics are aiming to resolve these issues by developing unique pulse transmission waveforms that all but eliminate lower frequency side lobes. Their goal is to monitor marine mammals at distance (up to 300 + meters) as they approach MRE sites and not have them aware of the acoustic signal (BioSonics, pers. comm.).

Field of view

Although the range of active acoustic systems is larger compared to other technologies such as optical cameras, when operating at higher frequencies this range is greatly reduced to achieve higher resolution images (1-5 m depending on the system). This is especially the case for systems such as ARIS (Sound Metrics). Therefore, it is still difficult to accurately track the movements and behaviour of marine animals over larger distances (60 m) and confidently identify them to species level while operating at higher resolutions.

Species level identification

The confidence and accuracy of species level identification using active acoustics is much lower when compared to other monitoring techniques such as optical cameras and other direct visual observations. In the case of acoustic cameras and multibeam identification of species groupings i.e., marine mammal, seabird and fish may be the best option to categorise individuals recorded. In some cases, certain features may be able to aid identification, this may include size, swimming behaviour, fin characteristics and air pockets in feathers. Single beam echosounders provide an additional route for the identification of targets, but their constrained field of view or resolution make this of limited use for monitoring purposes.

Turbulence in the water

Data quality in turbulent underwater environments may be reduced, masking important ecological targets (Williamson et al., 2017), making the identification of features difficult (Fraser et al., 2017) and potentially causing false classification. For the deployment of acoustic systems in locations subject to large flows, acoustic imagery requires dynamic correction for water movement to remove distortion. This problem is more acute when cameras are looking across the tide, or at animals moving across the tide rather than looking along it or moving directly against the tide. Established detection algorithms can fail in the dynamic environmental properties associated with marine renewable development sites. It is therefore important to remove turbulence from data sets using filtering, detection, and tracking algorithms (Williamson et al., 2017). Manufacturers such as Sound Metrics Corp have also included filtering such as background subtraction, crosstalk reduction and transmission loss as part of their software packages to enhance image quality in such instances (Sound Metrics Corp 2018). Additionally, background objects including the turbine itself or debris in the camera field of view may also distort images.

Data storage and processing

Large expensive data storage is required to meet the needs of long-term monitoring of acoustic systems deployed remotely without a direct connection to shore. Data removal in these instances rely on the schedule in which these active acoustic systems require maintenance. The vast amount of data recording during deployments of acoustic systems also poses a challenge for data processing. In some cases, data collection can be data rich, yet information poor (Cotter & Polagye, 2020). Automated analysis including machine learning so only 'events' are captured may reduce the data load and improve processing times. Machine learning in acoustics is a rapidly developing field for detecting patterns in data.

Although acoustic techniques have several advantages over optical imagery, confident classification and identification of targets is more difficult (Horne, 2000) and data processing methods to allow real-time target detection, tracking, and classification relative to current flows are currently under development (Hasselman et al., 2020).

As an umbrella term, active acoustic hardware outputs a wide range of types of raw and semi processed data. Data may be interrogated for measurements of distance, acoustic imaging, or relative returns from different wavelengths, all of which can be affected by ambient conditions including water temperature, salinity, turbidity, turbulence, and presence of gas bubbles as well as the orientation and size of targets being observed. Added to this, the range of uses of these data, from bathymetry and sub bottom characterisation as well as observation within the water column means that a number of approaches are needed to process data into the required information for the user's desired application.

For most applications, survey requirements are associated with the seabed and concerned with bathymetry and bottom type. The majority of surveying active acoustic processing software therefore are concerned with mapping processes. The monitoring of targets within the water column is a niche market, being primarily of interest to scientific research and commercial fishing communities, therefore software for processing is focussed on specific commercially important species and expensive to licence. For analytical purposes, the main commercially available software package is Echoview (Echoview Software Pty Ltd.), the purchase of a licence for which, that includes the capacity to process and identify targets in split beam and multibeam echosounders and acoustics cameras, costs in the region of £45,000 with additional maintenance licensing costs after the initial purchase. Free, community and institutionally developed processing packages are available, but these come with the added concerns of warranty, lack of documentation, lack of maintenance and questions about liability associated with their use with a non-commercial software package, which would be a major consideration on a large scale MRE development.

Power

Powering acoustic monitoring systems remains a challenge with preferred options including powering equipment using a shore-based power / fibre optic cable. For remote sites, a cabled connection to a surface buoy operating a solar array and cell modem or the inclusion of subsea battery canisters may be an alternative option. Battery services in this instance may be months apart.

6.6.5 Summary

Active acoustic techniques can be used to examine near field interactions (FR3) for all species groups in the vicinity of turbines, even in turbid, low visibility conditions. When associated with environmental or other monitoring data they can also contribute to other requirements (FR2, FR4, FR6).

Equipment is expensive and for longer term deployments early integration into turbine design is strongly recommended.

Although a range of limitations have been identified, most of these can be overcome with proper planning. The main issue which needs further progress is target classification, particularly at species level; using techniques such as AI tools this may be possible, but at the present time combining this technique with other tools and data to help identify targets is the best approach.

6.7 Tagging and tracking

Animal-attached data loggers are powerful tools used to quantify fine-scale space-use and behaviour. They are widely used in studies of fish, birds, and seals. Simple external markers can provide broad scale data on distribution and demography of animals. However, more sophisticated, integrated tags and sensors provide both quantitative information on potential for interactions and fine-scale, contextualised behavioural data, potentially in the vicinity of marine energy devices.

Cetaceans are difficult to catch safely, both for the animal and the operator, and as such, there are no cetacean tagging programmes currently undertaken in the UK. Studies elsewhere involving tagged cetaceans use animals that have been incidentally captured as by-catch, with collaborating researchers tagging animals before they are released (Johnston et al., 2005; Westgate et al.,1995). Other studies have used stranded animals that have been rehabilitated and tagged before release (e.g., Risso's, Shoham-Frider et al., 2002).

Several successful seal tagging studies have been carried out in the UK, predominantly on harbour seals with limited data for grey seals (Sparling et al., 2020). Seal pups can be tagged with external markers for looking at recruitment into adulthood (Pomeroy et al., 2010), whilst GPS/satellite tags have been used for providing telemetry data on at-sea usage at population scales (SCOS, 2013).

Seabird tagging studies are currently utilising archival integrated tags combined with GPS to provide data for parameters that are fed into CRM and agent-based models of avoidance. These animal-borne devices allow underwater movements of the individual to be reconstructed using pressure sensors, and behaviour can be visualised using accelerometers and magnetometers. This approach provides contextualised, high-resolution empirical data for diving birds and their 3D space-use, this method has been widely deployed across several species of interest. Analysing data collated from all tracking studies in the context of assessing the likelihood and nature of interactions between birds and tidal energy devices could provide useful data for developers within the sector, enabling them to mitigate any potential effects.

For anadromous fish species, Swansea University, working with the Atlantic Salmon Trust (AST) and the Game and Wildlife Conservations Trust (GWCT), in reports commissioned by NRW, have reviewed these systems in more detail (Clarke et al., 2021a) and have designed acoustic arrays covering the designated resource zones (Clarke et al, 2021b). The reports also contain recommendations for tagging studies to evaluate migration paths for the anadromous fish species identified in this report and to quantify availability of sentinel populations within the designated strategic resource zones for tidal stream, tidal range, and wave devices.

6.7.1. Marine mammals

Cetaceans

Although cetacean tagging is not undertaken in the UK, photo ID of cetaceans using unique markings and notches on dorsal fins can provide similar benefits to external markers for providing capture mark re-capture data for population estimates and site fidelity. This method is and has been carried out around Wales at locations such as Cardigan Bay Special Area of Conservation (SAC) where bottlenose dolphins have been monitored by NRW and non-governmental organisations (NGOs) such as Sea Watch Foundation (Feingold and Evans, 2013; Lohrengel et al., 2018). SeaTrust, based in Goodwick, Pembrokeshire, are the first organisation to trial this method on harbour porpoise around Strumble Head and Ramsey Sound, (H. Dunn, SeaTrust, pers comm., 2021). Photo ID has been carried out on Risso's dolphins off Bardsey Island, with data providing population estimates similar to national census and evidence of a level of long-term seasonal site fidelity (de Boer et al., 2013).

Seals

In Scotland, there have been numerous tagging studies on harbour seals. Satellite-Relay Data Loggers (SRDLs) were used in a large-scale national study looking at foraging behaviour of harbour seals around the UK (Sharples et al., 2012). This type of tag is relatively large (Table 3) and is made up of a data logger interfaced to an ARGOS transmitter unit, but also containing a pressure and conductivity sensor (Sharples et al., 2012).

SMRU have been developing telemetry tags for seals around the UK since 1988 (Plunkett & Sparling, 2015). Data transmission from these tags can be through the Argos satellite system (Argos tags) to give locations but they have also been developed to use a global system for mobile phone networks (GSM - phone tags). Both types result in location fixes, but data from phone tags have been found to be of better quality, providing more frequent locations (Plunckett & Sparling, 2015). These GPS-GSM telemetry tags are the best way of determining seal distribution at sea (Carter et al., 2020). These tags were used on harbour seals around Strangford lough to see habitat use before and after the SeaGen tidal turbine was deployed (Joy et al., 2018; Sparling et al., 2018). The tags are glued onto the fur on the back of the neck of hauled-out seals, which then become detached during the moulting season. This method was also used on harbour and grey seals around the Orkney Isles (Brims tidal energy lease area) over several years to provide dive depth data for determining water column usage (Evers et al., 2017).

Telemetry data of this kind can be used to create collision risk estimates for seals around tidal turbines (Thompson et al., 2016) and provide evidence of fine-scale habitat use of high tidal energy areas. For example, grey seals were found to avoid high current areas in Strangford Narrows (SeaGen site) (Lieber et al., 2018), and tagged harbour seals in Strangford Loch were found to favour slack water to fast flowing water when in the vicinity of the SeaGen turbine device (Sparling et al., 2018). This study also found that although the device itself did not lower presence of harbour seals, they did demonstrate avoidance behaviour when the device was operational, transiting at 250m either side (Sparling et al., 2018). SMRU instrumentation, UK provides a range of biotelemetry tags and visualisation software, details are listed in Table 3.

Table 3. List of satellite and phone tags developed by SMRU Instrumentation, UK, including specification.

Tag type	Details	Specification
Argos SRDL - (satellite relay data logger)	Relays location using Argos Global satellite system, sample of detailed dive records, depth, temperature, and speed.	Longevity: 1 year Size: 10.5 x 7 x 4 cm Weight: ~370 g
Argos CTD	SRDL features plus: oceanographic quality temperature and salinity.	Longevity: up to one year Size: 10.5 x 7 x 4 cm Weight: 545 g Volume: ~250 cm^3
GPS Phone Tag	GPS quality locations at user-defined rate (Fastloc). Detailed individual dive and haul-out data. Uses GSM mobile phone network.	GSM engine: Cinterion BGS2 module GSM bands: 850 MHz, 900 MHz, 1800 MHz, 1900 MHz. Size: 10 x 7 x 4 cm Weight in air: 370 g
GPS SDRL	GPS quality locations at a user-defined rate. Relays an unbiased sample of dive and haul-out records. Depth and Temperature.	Longevity: typically 3-6 months. Size: 10.5 x 7 x 4 cm Weight: ~370 g
Low Profile SRDL (Argos)	Data relayed (locations) via Argos satellite system. Unbiased sample of individual dive records. Temperature and depth.	Longevity: potentially up to two years. The battery of AA cells used in the Low Profile SRDL can provide up to 60,000 Argos uplinks. Size: 102 x 72 x 4 mm Weight: ~305 g Volume: ~180 cm^3

Archival tags, including accelerometer, GPS, and TDR, have been developed for use on grey seals, with research on best attachment locations for reducing drag detailed in Kay et al. (2019). Grey seals from Ramsey Island have been tagged by researchers from Swansea University and SMRU, although limited data has been recovered so far (W. Kay, pers. comm., Swansea University, 2021).

High frequency acoustic pinger tags with acoustic receiver arrays could also be considered for quantitative studies (see fish section below). These are extremely small and light (weighing as little as 0.28 g) and can have a life of 12 months or more.

6.7.2. Seabirds

Capturing and equipping seabirds with data loggers is almost always limited to the breeding season when colonial nesting birds are accessible on land. This limits the window of opportunity for collection of movement data with integrated tags which require temporary attachments and may only be fitted to the bird for a brief period of the season. Simple sensors, such a Global Location Sensor (GLS) or Time-Depth Recorder (TDR), which can be fitted to a permanent Darvic ring, can be equipped for several years with a good recapture rate, providing some longer-term insight into broad-scale space-use and diving behaviour. Tagging remains a powerful tool for monitoring the movements and interactions of ubiquitous seabird species.

For seabirds, permanent markers such as metal-alloy rings engraved with unique alpha-numerical codes or coloured Darvic rings enable identification of individuals when at a colony or found moribund/dead. These methods are particularly useful for extracting historical population trends, monitoring changes in demography (Peach et al., 1999) and measuring the population level effects of stochastic environmental events such as mass mortality of seabirds from oil spills (Birkhead et al., 1973; Stowe, 1982). Large numbers of seabirds are fitted with rings annually and have been since the 1930's (Harris et al., 1999). Some populations of seabirds in Wales are incredibly well marked e.g., Manx shearwaters from Skomer Island and common guillemots from Puffin Island., their demography is well studied, and the islands are more readily accessible than other colonies. Equipping these populations with data-loggers can complement broad-scale demography data with fine-scale data on spatial-use and behaviour.

Data storage or archival tags have been used extensively to study large-scale movement and behavioural patterns of marine animals. Rapid advances in archival tag technology (smaller cell size [CE2], increased memory capacity and lower cost) allowed gathering information on a wide variety of open ocean animals including mammals, seabirds, and fish. Tags can be light (1.3-20 g) and are most often implanted or secured externally on the dorsal part of the fish or attached via Tesa tape to the contour feathers of birds. Archival tags can record abiotic parameters such as pressure, ambient light, external water temperature and magnetic field as well as parameters like internal body temperature, heart rate, swimming velocity and tilt.

Data storage tags have been utilised for many seabird tracking studies over the last decades since their conceptualisation (Hatch et al., 2000; Wilson et al., 2012, 2010). Seabirds are well-researched study systems in this regard as they are conspicuous at sea when flying and colonial nesting, which facilitates efficient capture and recapture of marked individuals. External tags placed onto the animal which store GPS locations in the device's internal memory, enable other sensors to be incorporated- provided that the weight remains less than 3 % of the animal's mass, and importantly for diving birds, that the shape of the device is streamlined and has a low drag-coefficient (Vandenabeele et al., 2012). GPS has advantages over other archival-positional sensors, such as geolocators, in that they are suited to tracking seabirds over short ranges (where there is slight change in latitude), they are smaller with reduced power requirements and can quickly receive satellite signal during periods where there this may be intermittent i.e., when a bird is diving repeatedly (Phillips et al., 2004).

Time-Depth Recorders (TDR) are commonly used for studies of seabird diving behaviour, they collect information such as temperature, pressure, and depth. Tri-axial accelerometers provide behavioural insight, visualising animal movement through dead-reckoning (the reconstruction of animal movement trajectories) (Wilson et al., 1991) and are particularly suited to the study of marine birds in that the effects of current drift in highly tidal areas, can be corrected for in the resultant GPS track (Ryan et al., 2004).

A combination of all or most of the aforementioned sensors into one sophisticated tag is providing contextual behavioural and place-based data for seabirds and can allow insight into how they behave in tidal stream environments whether interactions with underwater devices may occur. The dive depths exhibited by seabirds ultimately indicate the degree of overlap to which they may interact with underwater devices (Furness et al., 2012; Johnston et al., 2018) and so visualise seabird movement in the 3D environment, in combination with accelerometery and other sensors this can give a clear picture of their space use. Studies using these types of tags provide direct data which feeds into parameters of collision risk and avoidance models e.g., dive depth, number of foraging trips, and time spent at specific depth intervals. When used to monitor birds from colonies close to MRE deployment areas, archival tags can provide baseline data and could be used to observe behavioural changes in response to developments.

In Wales, several studies of this kind have taken place; Cole et al., (2019, unpublished) tagged common guillemots from Puffin Island (Figure 7) with tri-axial accelerometers, GPS, and TDR. The birds were shown to be using areas of high tidal velocity and foraging around the Morlais demonstration zone. These birds were shown to be diving to depths greater than 35 m and foraging on the seafloor and in the mid-water column. Unexpectedly, the data showed significant nocturnal diving activity in these tidal stream environments. Without this data, these nocturnal behaviours are not observable. The Royal Society for the Protection of Birds (RSPB's) FAME (future of the Atlantic marine environment) and STAR (seabird tracking and research) projects have tagged multiple species of seabird since 2010 to look at at-sea distributions and broad-scale space-use from several important colonies across the UK (Wakefield et al., 2017). This data has the potential to be analysed in the context of investigating fine-scale habitat use of seabirds within resource areas as some of the animals were equipped with accelerometers and other integrated tags. A review of this collated data is currently being undertaken in the context of interactions with fisheries: It is a core ORJIP Ocean Energy priority to utilise any existing data to fill knowledge gaps and inform the MRE sector and so a study akin to this would be beneficial.

Figure 7. Photo of a guillemot being equipped with an integrated data logger, Puffin Island Anglesey (Emma-Louise Cole 2019).

The requirement to recapture birds to retrieve the data-logger can be a limiting factor affecting the efficacy of this tagging method, though some tags are able to download information to remote base stations. Good retrieval rates can be obtained from well-researched colonies with easy access and experienced bird ringers, but there is only a small window where nesting birds will be chick-rearing and therefore able to be captured and recaptured before they are unattainable at sea. Attachment methods are also limiting and must be carefully considered as to not hinder the diving bird. Device placement must also be performed accurately. Rigorous protocol and licensing are required for bird handling and special-methods permission must be obtained from the British Trust for Ornithology (BTO) before conducting deployment of bird-borne data loggers.

High frequency acoustic pinger tags with acoustic receiver arrays could be considered for quantitative studies (see fish section below). These are extremely small and light (weighing as little as 0.28 g) and can have a life of 12 months or more.

6.7.3. Fish

External marker tags are widely used in fisheries research and include tags such as Carlin tags, floy tags, dye marks and eye tags; NRW continue to tag fish in this way on the Dee index river in North Wales. Historically they have been widely used to generate mark-recapture estimates of anadromous migratory populations, though PIT (Passive integrated transponder) tags are now more widely used. Migration pathways can also be established using these techniques, provided a commercial fishery exists to provide recapture information. There are many such studies of commercially exploited marine species, often undertaken by Government bodies for fishery management purposes. For example, Picket and Pawson

(1994) describe migration pathways of European seabass *Dicentrarchus labrax,* in the English Channel and up the West coast of the UK, with much of the data derived from external tags recaptured in external fisheries. However, for the migratory species which are identified as the priority by ORJIP Ocean Energy, there are few commercial fisheries in the Welsh coastal zone to provide recaptures, and little or no information on migration paths.

Acoustic pinger tags are widely used in marine fisheries research (Thorstad, 2013b). They can provide information on individual fish distribution, migration rates, and population-level survival rates. They can also enable identification of critical marine habitats and periods (Chaput *et al.,* 2019). With good experimental design they can also be used to quantify the proportion of tagged animals and their residence time in a resource area, or in the immediate vicinity of a specific development.

Pinger tags transmit a unique code which identifies the individual animals and are detected by passive fixed hydrophones (receivers). Detection range is dependent on frequency, power output of the tag, and environmental conditions (noisy environments tend to reduce detection range). Consequently, detection range can vary from 50 m to 1 km. In marine studies receivers are typically deployed as fixed lines, fences or in matrix arrays. The location of the fish is identified by the location of the receiver; however as with PAM, with appropriately accurate receiver clock synchronisation and array design, fish location can be accurately determined in 3D if a single ping is detected by 4 or more receivers. With high density receiver arrays, they can provide fine scale positioning with accuracy of less than 1 m (Leander et al., 2020; Aspillaga et al., 2021).

Both receivers and tags are available as COTS products; tag life varies according to tag, but tags with multiple year life are readily available, enabling multi- year studies. The most used acoustic tags in the UK for marine studies are 69 kHz tags manufactured by Innovasea, with typical ranges of 200-400 m in normal conditions, though tags manufactured by Thelmabiotel are also used. An important constraint is that 69 kHz tags are within the hearing range of marine mammals and seals, so practical use is limited to deployments on fish.

Acoustic pinger tags are in widespread use to establish marine migration paths of the anadromous species of concern in this review, including Atlantic salmon, sea trout, twaite shad, and European eel. For example, Marine Scotland and the River Dee Trust have undertaken tagging of sea trout and salmon smolts, deploying more than 150 receivers to look at migrations in Aberdeen Bay, as part of investigations into the European Offshore Wind Development Centre (River Dee Trust & Marine Scotland Science, 2019). A range of migration studies are in hand looking at marine migration patterns of salmon and sea trout including studies by the Atlantic Salmon trust who plan to deploy some 800 acoustic receivers in the Moray Firth and off the West coast of Scotland. Other significant salmonid migration in the UK studies include the Sea Monitor programme, which is a consortium of nine partners from Scotland, Northern and Southern Ireland, led by the Loughs Agency. European eel has also been studied in marine environments with 69 kHz tags. Yellow and Silver eel life stage migration and behaviour have been studied by researchers including Walker et al. (2014) and Thorstad et al.(2013a).

Around Wales marine acoustic tracking studies have been limited although some studies of adult salmonids have been undertaken by NRW and their predecessors around Cardiff Bay and radio tracking studies have been conducted within estuaries. Equipment and example deployment options for 69 kHz receiver arrays have been described in detail in a separate report (Clarke et al., 2021b).

Far field movements and quantifying area use

Recently, Swansea University, working with the unlocking the Severn consortium have undertaken work on Twaite shad to evaluate the proportion of shad tagged in the River Severn utilising the Swansea Bay area throughout the year. This work has been undertaken to provide information which could inform and help calibrate modelling of the impact of the proposed tidal lagoon to generate power in Swansea Bay. Some 30 receivers have been deployed (Figure 8) with an outer receiver ring designed to be efficient and a number of receivers deployed within the ring to detect at least a proportion of the fish entering the Bay. This approach allows estimation of the efficiency of the outer ring by comparing the fish detected on the receivers within the ring with entry and departure events on the outer receivers.

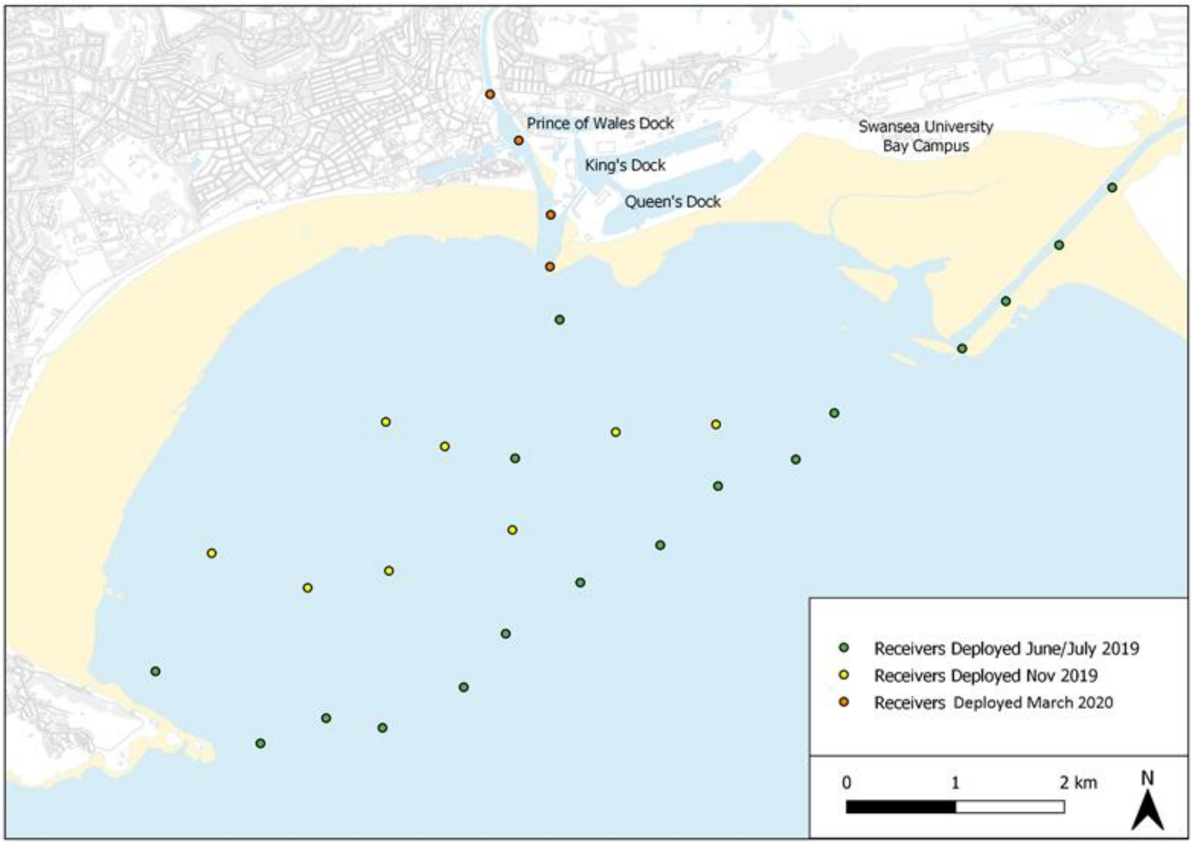

Figure 8. Map of Swansea Bay receivers, receivers deployed as an outer ring and inner ring. The northern cluster of receivers are deployed along the River Tawe.

The work has been extremely encouraging and has demonstrated that quantitative data can be collected on the proportion of the tagged population entering the Swansea Bay area, and therefore potentially at risk. These data can provide evidence on availability, residence time and factors such as tidal availability. Sea trout smolts and adults have also been tagged in the River Tawe and their movements tracked through Swansea Bay, to establish seasonal distribution and residence time in the immediate area. Similar studies could be undertaken with yellow and silver eels and it would be possible to use sensor tags (see below) to collect data on parameters required for modelling, such as swimming depth for sea trout, twaite shad and European eels.

More widely, this approach could be applied to any MRE (or other) development.

Fine scale applications

These systems can be used for fine scale tracking, with a sufficiently dense array.

With a sufficient receiver array density, 69 kHz acoustic tags and receivers can also be used for fine scale studies, including looking at movements in the vicinity of tidal turbines, and potentially the outcome of collision events. This approach is based on the detection of the signal by three or more receivers (four or more for 3D positioning). This allows the position of the tagged animal to be resolved using positioning algorithms based on the difference in the time of arrival of the signal (e.g., Baktoft et al., 2017; Steig and Holbrook, 2012; Li et al, 2014). Accuracy is based on a range of factors, including environmental noise and temperature, clock resolution, and the positioning method Melnychuk (2012). Accuracy and usefulness of tracks for this purpose is also affected by the transmission rate and the length of the ID transmission. Shorter intervals between transmission allow better track resolution, and shorter tag bursts allow better accuracy, as the animal is always moving.

Recent developments of high frequency tags (180 and 307 kHz for Innovasea, and 416 kHz for Lotek) have allowed improved fine scale accuracy. These frequencies have lower range in marine environments, which significantly reduces their value in anything other than fine scale studies. The tags, however, use very short transmission bursts (milliseconds) which allows better positional accuracy in fine scale studies, with 3-dimensional accuracy of less than one metre theoretically achievable (Leander et al., 2020). They are also less affected by background noise in turbulent environments such as those found in the vicinity of turbines. Directions. A comparative study of Innovasea PPM and HR2 (307 kHz) systems found that the HR2 system was less sensitive to background noise, achieved better than 1 m accuracy and was more accurate than the PPM system (Leander, 2020). In a fully marine study using the JSATS system (Aspillaga et al., 2021), used 70 acoustic receivers (approximate cost £2 k each), to cover an area 600 m x 270 m. Receivers were placed at 50 m spacing, and they successfully tracked more than 100 fish (tags are £140 each) with an accuracy of a few metres.

The main constraint on fine scale tracking to determine near and far field behaviour of migratory fish is the lack of certainty that tagged animals will enter the turbine field in question. This can be addressed by initial far field studies similar to the Swansea bay example described above, using coarser array grids. These studies have two benefits. If they demonstrate that few animals are using the development area, they can provide confidence that impacts are likely to be low and further investment is not required. If significant numbers of animals are using the area, then the practicality of fine scale studies can be confirmed and further investment in fine scale monitoring may be justified.

For example, in the Swansea Bay tidal range example described above, of 91 tagged twaite shad leaving the River Severn in 2019 more than 30% entered Swansea Bay, some many times, resulting in over 270 entry events. Of 46 sea trout tagged in the river Tawe, 25 were tracked through the bay and 8 re-entered on multiple occasions. Therefore, if a tidal lagoon were constructed, deployment of a fine scale acoustic array in the vicinity of the turbines and intake sluices, and incorporating receivers within the impoundment itself, would be expected to yield a good amount of data for migratory fish species such as Atlantic salmon, sea trout, twaite shad, eels, and lamprey. This would include both near and far field behavioural responses to the structure and its operation, as well as data on movement and passage survival of fish migrating in both directions.

Such an approach could be applied to other sites to collect the behavioural data recommended by ORJIP Ocean Energy (2020) if wider scale tracking demonstrated a reasonable likelihood of encounters. Practical deployment would require some testing to ensure adequate tag range in the environment around the turbine and tagging would require appropriate licencing.

For fish, the measurement of environmental temperature, light levels and magnetic field can be used to geolocate the individuals ‘back casting’ migration paths. Archival tags can record these various parameters, at a programmed rate (from a few seconds to several minutes), over periods of deployment of up to ten years. This level of data intensity allows determining an animal’s fine and large-scale behavioural patterns, migratory routes, and physiology response, all in relation to the surrounding environment.

The main limitation of archival tags is that they must be recovered to obtain the recorded data. For fish, this limitation restricts their use to species that have a sufficiently large fishery associated with them to ensure their eventual capture and return; or animals that return to specific sites such as rivers, with high fidelity. They have, however, been successfully used with a number of species, including sea trout kelts, to ‘back calculate’ marine migration paths from sensor data (temperature and depth). Some archival tags are embedded in a float and in some cases designed with a release mechanism (for external attachment) to allow the tag to drift at the death of the animal and be found on beaches. Pop up satellite archival tags have been used with large species. For fish, depending on the tagged species, the rate of archival tags found by the public on beaches can reach 20% of the tags deployed.

6.7.4. Tagging limitations

Although tagging is a valuable technique, it is important to understand its limitations. Firstly, enough animals must be captured for the objective, preferably representative of the population(s) which the regulators are concerned about. This is a particular issue when using tags with limited battery capacity for seabirds. Where tagging operations are focussed on capturing birds during the breeding season, difficulties may be encountered in catching animals on cliffs while minimising disturbance.

For quantitative studies, capture of enough animals is also necessary. For most fish species that may be practicable, but it may be more difficult for seabirds and depending on the nature of the tagging operation, for seals.

The tag and tagging process can sometimes influence the behaviour of the animal; tag induced effects and mortality can affect quantitative studies and this needs to be considered and accounted for when designing tagging protocol and subsequent monitoring.

There are ethical implications associated with capturing and instrumenting animals and Home Office licences must be obtained for most studies in addition to landowner's permission and other permissions from respective licensing bodies.

Data storage tags for fish (and in some cases seabirds) are large and the tags must be recovered for data to be downloaded. Some seabird tags transmit data to base stations but only if the tag records in bursts thereby loosing high-frequency continuous data.

6.7.5. Summary

Tagging studies are a valuable tool for collecting information on FR1, FR2, FR3, FR4 and potentially FR6. They can provide highly detailed and accurate movement information for both near and far field monitoring, including avoidance and potentially likelihood of strikes. For seals, seabirds, and fish they can provide detailed information on factors such as depth utilisation and swim speeds required to populate collision risk and avoidance models.

For fish species, given the small size of targets for acoustic detection and inability to undertake visual observations at the surface, acoustic tagging is the method of choice for collecting information on FR1, quantitative elements of FR2 and FR3, with sensor tags providing information on FR4. For fish, tagging studies can also provide the backbone of monitoring for tidal range studies with a particularly good prospect of success.

6.8. Blade-mounted sensors

Blade mounted sensors such as strain gauges and accelerometers are routinely fitted to tidal turbines as part of the condition monitoring system and are usually continuously monitored through the supervisory control and data acquisition (SCADA) system. Strain gauges are used to measure bending or flexing of the turbine blade. Developers are experimenting with using them to detect collisions with marine animals. Many of the devices testing at European Marine Energy Centre (EMEC) and MeyGen in Scotland have strain gauges installed (e.g., MeyGen, Sabella, Orbital Marine Power, Voith Hytide) and DeltaStream, Ramsey Sound. Initial results, however, have suggested that there have been so many events that it would not be possible to differentiate between background turbulence and a collision event (Hutchison et al., 2020).

Accelerometers have also been used as part of the condition monitoring system and measure the acceleration and vibration encountered by the turbine blades. Accelerometers are being tested to detect collisions, but limited data has been reported on their effectiveness. Because of the relative mass of turbines and marine animals, it is likely that accelerometers will only be effective at detecting larger objects such as marine mammals or larger fish species such as sharks and distinguishing these from other natural objects remains problematic.

It may be possible to integrate a number of sensors and technologies into a multisensory system to detect collisions. Hydrophones installed on the external structure of a turbine device and microphones installed inside the turbine body are also being explored as a method of detecting the sound during an impact event. A combination of strain gauges, accelerometers, hydrophones, microphones, visual and acoustic sonar technologies could be incorporated into the system. Machine learning could be used to integrate sensors into an automated impact detection system, this work has been done on wind farm turbines with promising results (Hu & Albertani, 2019) but would require dedicated future research in the marine tidal sector if problems are to be overcome surrounding the turbulent hydrodynamic environment of tidal stream energy sites.

6.8.1. Summary

Although blade-mounted sensors have the potential to provide information on collision events, there is little evidence of their success and reliability at detecting real world collision events on tidal turbines in the literature. Nevertheless, these technologies are routinely integrated into the turbine structure as part of the condition monitoring system and could pose an area for further research. With further research, it may be possible to overcome some of the challenges by developing effective algorithms that can extract an impact signal from the noisy background.

These technologies are not ready to detect collision events reliably, especially for fish and diving seabirds, which are likely to be too small to be detected. It is also not clear how effective these sensors would be at detecting indirect hits on larger marine animals. If these sensors are unable to reliably detect indirect hits even on larger marine animals, then their usefulness as a tool for detecting collision events is extremely limited, as an indirect hit could potentially have lethal or sub-lethal consequences.

6.9 Integrated technologies

Several research groups have recognised that using a range of devices in a compact integrated system approach may provide a better and more inclusive overview of interactions of marine animals with turbine devices. Combining data from various sources, such as multibeam sonar, echosounders, acoustic doppler current profilers (ADCP), passive acoustics (hydrophones, fish tag receivers), optical underwater cameras (HD and artificial illumination), and deep - learning algorithms can add synergistic value. For example, some integrated systems link echosounder and multibeam data in real time to improve target tracking and to provide triggers for optical cameras (Bicknell et al., 2016; Wilby et al., 2016).

As an example, the Adaptable Monitoring Package (AMP) (Figure 9) has been under development since 2011 with more than 7 deployments and over 2 years of in water operations for monitoring ecological interactions with underwater turbines (Polagye et al., 2020). Developing this type of equipment is costly; AMP-related projects have received a few million (USD) in support of equipment acquisition, system development, deployments/recoveries, and other project related tasks. We have been advised that this is a reasonable guideline for the costs of developing new systems for operations in similar applications.

The Flow and Benthic Ecology (FLOWBEC) 4D platform has also been developed using Natural Environment Research Council (NERC) funding to monitor how hydrodynamics and prey movements may be influencing predator behaviour at high tidal energy sites (Williamson et al., 2016). FLOWBEC uses a number of integrated devices including ADCP, single-beam and multibeam echosounder with the potential for the addition of other monitoring units such as hydrophones. Since 2010, there have been over 6 deployments providing baseline and device presence data. The platform can be adapted to answer different monitoring questions. For short-term focused surveys, specialised battery packs attached within a subsea frame has been developed for quick deployment and retrieval. If intended for longer-term monitoring, the platform can also be cabled through the MRE device. There is also the possibility that it can be deployed pointing downwards from a survey platform or a moving vessel. The FLOWBEC system is one of the only integrated platforms that has been successfully deployed in high tidal flow (up to 4 m/s) and the use of a ping synchronisation interface to avoid acoustic interference between sonar devices.

In recent years, SMRU have developed the HiCUP (High Current Underwater Platform) which has a tripod-based design allowing stable deployment of monitoring equipment on uneven surfaces. The system has been deployed with high frequency multibeam sonar equipment mounted to detect and track seals within a tidal channel on the west coast of Scotland (Hastie et al., 2019). The sonar HiCUP platform is currently being configured to the turbine connection at the MeyGen site, comprising two sonars to enable coverage of the full height of the turbine (Hasselman et al., 2020). The use of automatic classification algorithms that have been developed (Hastie et al., 2019), will reduce the level of manual screening and storage of large quantities sonar data.

Other integrated systems include the Fundy Advanced Sensor Technology platform developed by the Fundy Ocean Research Centre for Energy, the Integrated Monitoring Package developed by the EMRC, and “Plug & Play” under development by the SMRU at St. Andrews University (Polagye, 2020).

The adaptable monitoring package described by Polagye (2020) has to date been used in a research capacity. However, after communication with the research group during this review, evidence suggests it has undergone significant steps in its development toward a COTS solution. This is also true for the FLOWBEC system.

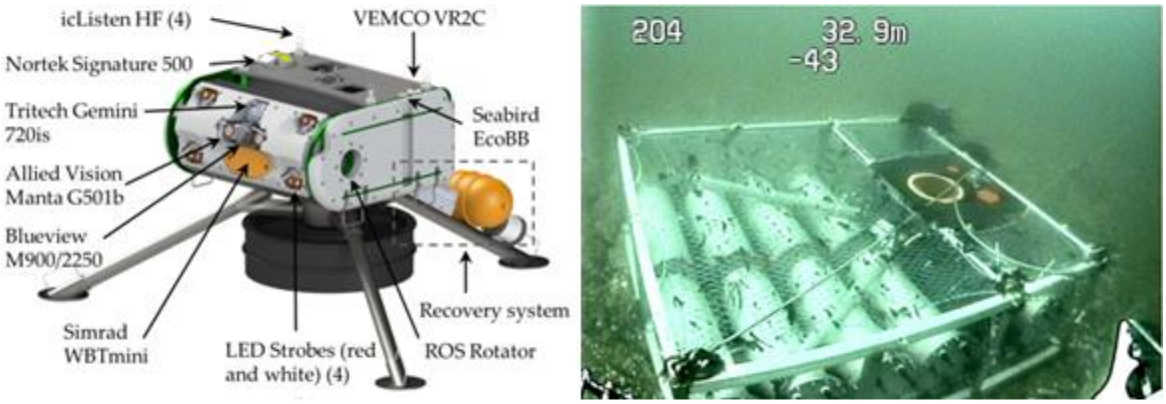

Figure 9. An example of an integrated monitoring system as described in Polagye (2020) on left, and image of the FLOWBEC subsea frame deployed at EMEC tidal energy site from Williamson et al. (2016).

One of the key challenges that remains in interpreting active acoustic data is target classification, particularly species level identification, and combining acoustic data with other sources such as PAM (for cetaceans), visual images or surface observations, to create acoustic datasets describing the characteristics of known targets, is key to improving automated classification algorithms. Real time ADCP flow data can also be compared with multibeam target movement data to help distinguish live biological targets (this approach was used by the Ramsay Sound DataStream deployment).

Integrated target identification can also reduce the amount of data storage required for monitoring turbines as the cameras are not continuously filming. Ultimately, reducing the amount of 'irrelevant' data recorded, reduces the processing time and any costs associated with this. Additionally, the introduction of deep-learning algorithms into these systems can reduce the manual analysis of data. Machine learning technologies can be applied to the analysis of image and video datasets (Ditria et al., 2020).

There are no COTS integrated packages available that we are aware of. Although integrated data adds considerable value, when using integrated techniques, developers should not underestimate the potential electrical or acoustic interference between devices, the challenge of software integration and issues such as power supply and data storage.

However, several research groups have made considerable progress toward COTS solutions, successfully overcoming many of the basic problems associated with equipment integration, including electrical and acoustic interference between devices, and software integration.

6.9.1 Summary

Integrating data from various sources such as PAM, active acoustic, optical cameras, and environmental monitoring devices can add considerable value to observations.

Integrated modular packages such as FLOWBEC, HiCUP and AMP have been developed by a number of research groups using grants and other funding and have now been used in multiple deployments for each device. These packages have had to overcome system integration problems including software control development, interference between electronics and different acoustic elements of the package, synchronisation of signals to avoid interference, power, and data storage. Broadly the more developed packages have overcome these problems, although they could not yet be described as commercially available (COTS) products. These packages can either be deployed integrated into a device (which requires early-stage design involvement) or stand-alone packages which will require careful planning of moorings.

In the turbid conditions around Wales, combinations of this type may be the only effective way of looking at nearfield avoidance behaviour, or potentially turbine strikes, (although observing strikes is at the limit of what is achievable). They have the potential to identify and track and, in some cases, identify larger animals, such as marine mammals and seabirds. They can also be used to observe fish movements, although species identification is unlikely in the absence of visual observation.

Table 4. The benefits and constraints applicable to the suitable technologies available to monitor species groups in Welsh waters.

Technologies available	Functional requirement	Species group application	Technology	Benefits	Constraints
PAM	FR1, FR2	Cetaceans	Hydrophones C-POD/F-POD	– Fixed, drifting, towed hydrophone – Provide presence/absence data – Species identification – Spatial and temporal distribution – Background noise and avoidance behaviour – Non-invasive	– Can produce large datasets – CPODS are autonomous and so cannot provide live data feed at present
PAM arrays, Bespoke PAM devices	FR1, FR2, FR3	Cetaceans	Hydrophone array	– C-POD/F-PODs have minimal data storage issues. – Hydrophone clusters/arrays can track animal movements at close range and give 3D distribution within water column	– Hydrophones can produce large datasets and need specialist analysis. – Hydrophone clusters are custom built for purpose
Optical cameras	FR1, FR2, FR3	Fish, marine mammals, seabirds	Underwater camera / video	– Capable of species level identification – Observe animal movement and behaviour – Ability to corroborate other sensors – Potentially confirm collision events	– Limited by water clarity and light availability – Can be labour intensive, although machine learning can reduce this limitation
Visual Observations	FR1, FR2	Marine mammals, seabirds	– Vantage point (land based) and boat-based surveys – Photo ID, Vector binoculars, 3D video tracking, laser rangefinder – Ornithodolite	– Track individual animals, site specificity – High precision and resolution – reconstruct movement tracks – Simple data collection and processing, link with historical datasets	– Weather constraints – Daytime observations only – Labour intensive

Technologies available	Functional requirement	Species group application	Technology	Benefits	Constraints
Visual Observations (Aerial)	FR1, FR2	Marine mammals, seabirds	– Manned aircraft – UAV	– Manned aircraft: Distribution over large areas – UAV: Cost effective, fine-scale distributions	– Above sea surface only – Weather constraints – Daytime observations only – Manned aircraft: High cost, limited movement, and behavioural information
Active acoustics (multibeam / Imaging Sonar)	FR1, FR2, FR3, FR4	Fish, marine mammals, seabirds	Multibeam / Imaging sonar (>200KHz)	– Target detection and tracking of biological and non-biological targets in the water column – ARIS: Potential for direct observation of fish interactions	– Limited range (<60m) – Large amounts of data created – Species level classification is low
Active acoustics (single / split beam)	FR1, FR2, FR3	Fish, marine mammals, seabirds	single or split beam transducers. (<200KHz)	– Distribution of fauna in the water column – Backscatter and Target strength values allow some level of species classification – Longer range than multibeam imaging sonar – Split beam transducers can locate targets in both vertical and horizontal plane, effectively allowing 3D tracking of targets	– Mapping prey distribution does not account for animals transiting an area when not feeding – Lower frequency transducers have been shown to effect marine mammal behaviour
Acoustic tags / acoustic receiver array	FR1, FR2	Fish	–69kHz systems - High frequency acoustic tags (180, 307 and 416 kHz)	– 69 kHz Acoustic tags and receiver arrays for quantitative assessment of sentinel stocks – high frequency tags have improved fine scale accuracy and are less affected by background noise	– Need to tag enough for quantitative results – High frequency tags have limited range compared to the 69kHz systems
Telemetry / Bio-loggers	FR2, FR4, FR6	Seals / seabirds	Satellite-Relay Data Loggers	– Quantify space use and behaviour – Can incorporate GPS, pressure, depth	– Ethical implications. – Bias toward animals easy to tag, animals

Technologies available	Functional requirement	Species group application	Technology	Benefits	Constraints
			(SRDLs) Radio tags	& accelerometer sensors – Assess behavioural response / barrier effects	may not enter area of interest – Logistical issues with capturing and tagging animals – small sample size
RADAR	FR1	Seabirds	marine X-band radar	– Ability to detect and track seabirds over wide areas and extended periods (including night-time), (McCann et al., 2017)	– Detection is negatively affected by sea conditions – Cannot account for target altitude, but potential to distinguish between flying and floating seabirds using tracking algorithms combined with surface current information
eDNA	FR1, FR2	Fish, marine mammals	eDNA is standard metabarcoding / sequencing.	– Provide presence/absence data and enable a strategic baseline to be established for a range of species and purposes	– Need to assume a threshold minimum for absence (=detection level) – Wide area rather than precise tool
Blade mounted sensors	FR3	Fish, marine mammals, seabirds	– Accelerometers – Strain gauges	– Possibility of using turbine condition monitoring sensors already installed for collision detection	– Low ability to reliably detect impact with an animal due to high vibration and flex in turbine blades – Signal processing algorithms need further development – Likely to only detect collision with large animals and not birds or fish – Unable to identify to species level

7. Costs

Costs in this section are intended to provide an overview of scale and enable comparison of relative costs of different techniques. In practice a major proportion of monitoring costs are linked to factors such as vessel hire for deployment and retrieval of equipment, and these will vary according to vessel availability, equipment deployment needs, and working conditions. Survey design will also vary according to site, scale, functional requirements, and species, which will also significantly affect costs.

For these reasons, costs provided in this section should be viewed as a guide to the likely scale of costs and should not be relied on for design of individual surveys. Indicative costs for the main equipment type are summarised in Table 5.

7.1. Vessel costs

Vessel costs vary according to capability and circumstances. Where equipment is built into a turbine or platform, it is likely that deployment costs will be incorporated into the costs of deploying the device itself.

Deploying and maintaining smaller remotely deployed equipment such as C-POD/F-PODs, SoundTraps or acoustic receivers can normally be undertaken using smaller craft such as fishing vessels or smaller commercially coded inshore vessels. Around Wales these can normally be hired for around £800-£1,500 per day plus fuel.

The deployment of larger devices such as integrated monitoring devices is dictated by the weight of the device (including moorings) and the lifting capability of the vessel. As an example of this, deploying an integrated monitoring device for bottom mooring in strong currents would require a 2-tonne lift; based on our own recent experience, vessel costs for deployment would be around £2,500 plus VAT (Value Added Tax), assuming the deployment could be undertaken in a 12-hour day.

Prices for vessels with more extensive lift capabilities can be much higher and will often include mobilisation (getting to site) costs. Fully equipped research vessels such as the Irish Marine Institute's Celtic Explorer can cost in the order of £1,500-2,000 per day.

7.2. eDNA strategic survey costs

Indicative costs for carrying out a survey covering all the identified Resource Areas (6 sites, 2 weekly sampling for 12 months), for one species group, is estimated at £400,000 for metabarcoding and Sanger sequencing of 8 migratory anadromous fish species. This includes vessel time to deploy and retrieve samplers, sampler hire, sampling materials, sequencing, analysis, and reporting. Additional costs for other species groups would be of the order of £28,000 or £48,000 for metabarcoding and Sanger sequencing, respectively. Sampling costs would not be duplicated.

These costs are based on the method used by Mynott and Marsh (2020).

7.3. Optical cameras

The costs of optical cameras vary depending on specification, make and model. Inexpensive compact cameras and camcorders can range anywhere between £100 to £1,000 but are restricted by battery power and data storage. Mains powered underwater cameras such as those previously applied to long term turbine monitoring programs can range anywhere between £200 to £30,000 excluding any other deployment requirements or accessories such as data storage and power facilities. While camera technology can provide reliable results in the right circumstances, the use of optical cameras is only recommended if water quality sampling demonstrated that the deployment area had good visibility.

7.4. Visual surveys

The costs for marine mammal observers, land or boat based, is likely to be £250-£350 per day dependent on experience. Taking a mid-range level of £300 per day, land-based surveys with a minimum of 2 observers at each vantage point, would cost from £600 per day. Boat-based surveys require a minimum of 4 observers so costs would be ~£1,200 per day plus the cost of vessel hire. Dependent on survey design and what data is already available, surveys are likely to be carried out seasonally.

The costs associated with conducting visual observations for seabirds are similar to that of cetaceans with shore-based vantage-point surveys requiring a minimum effort of 36 hours per ‘season’ (breeding/winter), broken down into 12 x 3 hr surveys, for pre-construction developments and costing around £200 - 250 per day for a freelance ornithologist. These costs may be marked up if employing a consultancy which would also include analysis and reporting. Transect surveys via vessel are more expensive costing around £300 - £400 for the ornithologist, of which a minimum of two are needed per survey; the boat transects must be repeated a minimum of twice per season and aim for coverage of greater than 25 % of the resource area. Visual observations and vessel surveys can only be carried out under certain weather conditions and sea states, and so the survey effort may be reduced if extended periods of unsettled weather persist. Again, vessel hire costs must also be factored into this.

Aerial surveys, combined with high-definition imagery, may sometimes be the most practical method for establishing seabird presence and abundance for developments that are further offshore and therefore out of range of standard optical equipment. The costs of these surveys are high; hiring of a suitable aircraft costs ~ £5,000 per day (costs may be higher if a larger area is to be covered), hiring of photographic equipment and staff time to process the images can cost upwards of £4,000 per survey.

7.5. Passive acoustic monitoring

7.5.1. Single units

Costs of C-PODS/F-PODS (Chelonia Ltd) are around £2,900 per unit. SoundTraps (Ocean Instruments, NZ) are £3,000-4,000 per unit.

High Tech Inc (HTI) have produced thousands of hydrophones for government and industry use. Their hydrophone/preamplifier units cost £1,170 each for the high frequency HTI-99-UHF model. These hydrophones are those recommended for use with the 4 channel SoundTrap recorders.

7.5.2. Hydrophone clusters

Ocean Instruments produce an off the shelf 4-channel recorder which can be used as a tetrahedral cluster for locating vocalisations. This costs £3,600 plus the cost of four suitable hydrophones (£4,680), totalling £8,280. Additional costs would include importation costs, the frames required for deployment which will be bespoke designs, testing, deployment, maintenance, and analysis.

Hydrophone cluster costs within the indicative AMP costs provided by Washington State University comprise just under £9,000, including integration (£7,250) and 4 hydrophones (£1,450).

Minesto have deployed two hydrophone clusters. They have advised that their equipment costs were £100,000 and that indicatively, the full cost of their deployments is likely to be £250,000 or more. This would include ca £100,000 equipment cost plus deployment and maintenance costs (ship and staff time) and costs of analysis.

7.5.3. Towed arrays and floating clusters

Swansea University recently procured a bespoke towed array for cetacean surveys, capable of directional location of cetaceans. Cost was ca. £18,000. Floating vertical arrays attached to a buoy or similar would be likely to be more expensive.

7.5.4. PAM arrays and maintenance costs

To illustrate the overall costs of a deployment, a PAM array deployment covering an area of 4 km^2, with 500m receiver spacing to ensure thorough overlap in detections would require 25 monitoring units. Using F-PODS, that would equate to £72,500 equipment costs and £5,000 in moorings (£200 per unit).

Based on our own experience, working around Wales it is desirable to retrieve and clean equipment every 3 months to limit biofouling and retrieve data. Assuming a 12-month deployment, this would require around £20,000 of ship time for deployment and maintenance (assumes 5 units serviced or deployed per ship day). At least one full-time employee, with appropriate skill levels, would also be required to prepare and manage deployments and maintenance, download, and analyse data.

This level of deployment would be expected to provide good quality data on cetaceans entering the area covered by the array, including coarse scale movements enabling an understanding of far and mid field avoidance. Understanding fine scale movements and potential impacts would require the additional deployment of hydrophone clusters (see above for costs) or an integrated device with both passive and active acoustic capability.

7.6. Active acoustic monitoring

Active acoustic systems (acoustic cameras) are more expensive than other technologies such as optical camera systems. There is a wide range of equipment available, with costs ranging from £25,000 to £275,000 depending on the device. Examples of some commonly used devices are:

Fisheries sonar (SIMRAD WBTMini/Simrad EK series) £36,000 - £50,000+

Multibeam sonar Tritech Gemini 720IS SDK £30,000-£35,000

Acoustic camera (Soundmetrics ARIS 3000) £80,000

Coda Octopus Echoscope -£250,000-£276,000.

Depending on the proposed use of data collected by these methods, additional processing software will be required to categorise detected targets. A one-year licence for the most used software package Echoview, costs an initial ca £15,000 with the opinion of service licenses after expiration.

7.7. Tagging systems

7.7.1. 69 kHz pinger and sensor tags

These are COTS products which are used in fisheries research, with a number of manufacturers. Indicatively pinger tags cost from £150-£265 per tag, and sensor tags cost from £250-£400 per tag depending on sensors.

Passive receivers for detecting the tags cost from £850-£3,000, with the most used receivers costing around £1,400. The higher cost units are fitted with acoustic releases for deeper water operation.

7.7.2. Fine Scale tracking (Innovasea HR and LOTEK JSATS)

These are primarily sold for fisheries work but could be applied to seabirds and seals. There are two systems, LOTEK JSATS and Innovasea HR. JSATS tags cost £130 and receivers £2,034.

7.7.3. Acoustic tracking arrays

Acoustic tracking receivers are deployed in fence lines or arrays. Standard 69 kHz receivers are typically deployed 400 m apart, though this will vary according to tag power and local conditions. For fine scale work using high frequency tags, receivers may need to be as close as 50 m apart in a grid around the site. Costs for different arrays around Wales are given in Clarke et al 2021.

7.7.4. Data storage and GPS tags (DST)

There are a range of well-developed integrated COTS tags for tracking seabirds, incorporating GPS, accelerometers, temperature/depth recorders and other features. Manufacturers include TechnoSmArt, Wildbytes technologies, Ecotone, Biotrack/LOTEK and PathTrack. Some tags must be recaptured, while others download data to base stations. Costs vary from £300-£900.

7.7.5. Satellite and phone tags

These are commonly used for seals. Specialist tags include those developed at Swansea University by Wildbyte technologies (including accelerometer, magnetometer (for movement) and barometric pressure sensor (for depth) cost £3,600 each. SMRU Instrumentation produce a range of satellite and phone tags suitable for use on seals, ranging from £3,500 to £5,000.

Table 5. Indicative costs of different survey techniques available.

Monitoring type	Example technology	Indicative cost range	Comments/assumptions
Survey vessels	Fishing, smaller inshore vessel with A frame and winch gear	£800-£1,500 per day	Suitable for deploying and servicing equipment such as C-POD / F-POD / Acoustic receivers. Limited lift capacity.
	Medium vessel	£2,000-£3,000 per day	Suitable for larger deployments such as remote integrated package deployment and moorings.
	Full RV capability	Up to £20,000 + per day	Suitable for larger deployments such as remote integrated package deployment and moorings.
eDNA survey	Continuous samplers, metabarcoding and sanger sequencing, analysis, and reporting	£400, 000 one off costs	Costed for strategic survey of 6 resource areas around Wales; 2 weekly survey for 12 months, includes vessel costs.
Visual survey	Marine Mammals	£250-£350 per day per observer £250-350 per day for analysis or report writing.	Vantage point obs. require a minimum of 2 observers so costs would be ~£600 per day. Boat-based surveys require a minimum of 4 observers so costs would be ~£1,200 per day.
	Seabirds	£200 - £300 per day for vantage point observations. £300 - £400 (x 2) per day of vessel survey (offshore)	Costed for a freelance ornithologist, may be marked up by a consultancy but this would include further analysis and reporting. A minimum of 2 observers are required for vessel surveys, including use of a suitable survey vessel with flight deck and minimum 5 m elevation. Costed per ornithologist.
Passive Acoustic Monitoring (cetaceans)	C-PODS/F-PODS	£2,900 per unit	Produces (initially) processed summary data. Excludes moorings and deployment, cost per unit.
	SoundTraps	£3,000-£4,000 per unit	Produces sound file. Excludes moorings and deployment, cost per unit.
	COTS Hydrophone cluster. 4 channel recorder (Ocean Instruments NZ)	£5,000 for recording unit + £4,800 for 4 hydrophones	Does not include bed frame, moorings, deployment etc.

Monitoring type	Example technology	Indicative cost range	Comments/assumptions
	Bespoke hydrophone cluster	£50,000	Figure from Minesto.
Visual cameras	Wide range of types and capabilities depending on requirements.	£100-£30,000	
Active acoustic monitoring	TriTech Gemini 720is - Multibeam	£25,000-36,000	Costs from Washington State AMP. Does not include bed frame, moorings, deployment etc.
	Blueview M900/2250-130-S-MKS(W)-MK2	£43,000	Includes sonar head, accessory kit and annual maintenance which provides access to the latest SDK software.
	BioSonics DT-X AMS (Automated Monitoring System)	£58,000 - £65,000	This includes AMS control unit, AMS power management unit, DT-X echosounder, transducer cables and single beam or split beam transducer. Used at the RITE project, New York, USA.
	Coda Octopus - Echoscope	£250,900 - £276,00 12-month rental from £120,00 Daily rental: £725	Prices range from Standard triple frequency Echoscope with underwater survey explorer software to the Triple frequency Echoscope PIPE with 4G USE Live & Replay and Sequencer Module. All prices include Pan & Tilt device, 3D Connect power supply and 75 m cables for sonar and Pan & Tilt.
	ARIS 3000 - High resolution acoustic camera	£80,000	May allow fish ID in some cases. Does not include bed frame, moorings, deployment.
	Imagenex – 837B Delta T multibeam imaging sonar	£13,600	Price per sonar head. Used on the FLOWBEC platform.
Acoustic Tagging systems	Acoustic pinger tags and receivers (69kHz)	£150-£250 per tag £850-£3,000 per receiver	Simple Id tags. Ping frequency patterns programmable. Suitable fish only. High end receiver costs include acoustic release. Long life (5-year deployment) receivers cost ca £14,000.
	Sensor tags	£250-£400 per tag	Depends on sensors; high end costs include depth. Suitable fish only
	High Frequency tags and receivers (LOTEK/Innovasea)	£130 (JSATS) per tag / £2,000-£2,800 per receiver	Fine scale tracking; fish and seabirds/seals. Excludes tagging and receiver deployment/maintenance costs.

Monitoring type	Example technology	Indicative cost range	Comments/assumptions
Seabirds - Data Storage / GPS tags	Wildbytes technologies / Ecotone / Biotrack /Pathrack	£500-£1,000	Most with GPS and sensors; some require tag recovery, some download to base stations (UHF/VHF).
Seals - Satellite and GSM tags	SMRU technologies	£3,500-£4,500 per	Excludes data charges and deployment costs.
Seals - Data Storage / GPS tags	Wildbytes technologies	£3,600 per tag	Excludes deployment and recovery costs, data analysis etc.
Integrated instrument packages	AMP (Washington State University)	£113,000-£250,000 per unit (see text for detail)	Remote deployment pick and mix, includes frames, integration software, cost depends on technology included.
	BioSonics Omni-directional long-range target detection and classification system.	£180,000	In development and testing at the WETS (Wave Energy Test Site) in Hawaii. 360° coverage from 48 sonar heads plus secondary sonar head for directed classifier.

7.8. Integrated assessment tools

7.8.1. Adaptable monitoring package (AMP)

Washington State University have helpfully provided a cost breakdown of the component parts of their AMP device (Table 6). This allows a 'pick and mix approach;' the highlighted components illustrate the costs of a PAM cluster plus Tritech imaging sonar totalling some £113,000. Adding in a visual camera, fisheries echosounder and seabed mountings brings the cost to approximately £240,000.

These costs do not include deployment, maintenance, recovery, or any of the data management/analysis. These costs would obviously be very deployment specific depending on vessel options, duration of deployment and operating environment. They recommend budgeting for one full time person to do the data maintenance and analysis for generating reports.

Washington State have also advised that the non-recurring expenses associated with developing the device, including 5 deployments were in the low $millions.

Table 6. Technology installed on the AMP device and associated costs.

Instrument/Component	Manufacturer	Unit Cost £	Quantity	Total Cost £
Imaging Sonar 1	Tritech Gemini	36,000	1	36,000
Imaging Sonar 2	Teledyne BlueView	25,200	1	25,200
Hydrophones	HTI	1,440	4	5,760
PAM Integration Array	Custom	7,200	1	7,200
ADCP	Nortek Signature	21,600	1	21,600
Echosounder	Simrad WBTmini	36,000	1	36,000
Rotator	ROS P-25	14,400	1	14,400
Optical Camera System	Custom	36,000	1	36,000
Integration Hub	Custom	21,600	1	21,600
Cabling	Subconn/McCartney	7,200	1	7,200
Instrument Mounting Frame	Custom	14,400	1	14,400
Bottom Lander	Custom	14,400	1	14,400
Total of everything (assumed exchange rate; 1USD=0.72GBP)				£239,760
Total highlighted:				£113,760

7.8.2. FLOWBEC and HiCUP

The FLOWBEC monitoring platform has been developed out of NERC funded research and 10 years of research and development work. As with the AMP, costs are dependent on the platform design and the components selected.

HiCUP platform, is custom made dependent on monitoring equipment attached, but costs not available at present.

8. Discussion and conclusions

The scope of this project requires investigation of available and emerging monitoring techniques to assess far and near field effects of tidal turbines and tidal range schemes on marine mammals, seabirds, and fish, and to provide recommendations on those most suitable for use in high energy environments in Welsh waters.

8.1 Challenges

Sites suitable for the deployment of tidal stream and tidal range devices are likely to be dynamic environments, which is applicable to much of the Welsh coast. Resource areas for tidal stream deployments exhibit high current velocities, turbulence and in many cases, are exposed to significant wave action. All monitoring devices deployed to look at tidal interactions therefore must function in that environment. Two issues also arise in the waters around Wales, high turbidity (limiting underwater visibility) and biofouling. These factors are important context for the selection of monitoring techniques and the choice of devices which are to be deployed. We briefly describe them below.

8.1.1 Tidal velocities and turbulence

Many of the monitoring techniques currently deployed to look at near and far field interactions were developed for broader use, and the dynamic environments around turbine sites are challenging. This impacts the equipment itself; both in terms of requirements for robustness and through the effect of tidal noise and turbulence as well as turbine noise interfering with, and reducing effective range of techniques such as PAM, active sonars, and tags.

Tidal velocities also affect mooring requirements for both seabed and surface deployments of monitoring equipment, as well as working windows for general deployment, ROV's, and dive teams. Equipment requires heavy duty moorings and, in many cases, custom frames for deployment in these environments. That has the effect of increasing the ship time required for deployment and maintenance, and in some cases influencing the capabilities of the vessel required to undertake the work. Both these factors increase costs as compared with operating in more benign environments.

8.1.2 Turbidity

Coastal waters around Wales are subject to large tidal ranges and high velocity currents which in turn increase underwater turbidity levels through suspended sediments in the water column (Jones 2020). SPM levels in parts of the Welsh coastline are extremely high, with the Bristol Channel averaging surface SPM levels of >30 mg/l between 1998-2015. This area includes Swansea Bay and the Severn Estuary. Parts of West and North Wales have also been identified as averaging surface SPM levels 10-15 mg/l between 1998-2015 (Silva 2016). Visibility in areas such as the Morlais development area and Holyhead deep are also poor (M.J Roberts, pers comm). Consequently, camera techniques are more suited to general presence/absence surveys rather than for collision monitoring (Jones et al 2019; Jones et al., 2020). This limits the use of optical camera methods for monitoring direct collisions with tidal turbines; sonar or acoustic cameras are more appropriate techniques for use around Wales. Factors such as season (algal blooms), tides, water currents, depth, and sediment composition at any proposed tidal turbine development location should also be taken in to account if considering the use of underwater cameras.

8.1.3. Biofouling

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, comprises a variety of species depending on the location, depth, and configuration of the structure (Coy, 2016). If fouling occurs, the field of view of optical instruments may become obscured, reducing the ability to observe animals (Hutchison et al., 2020). Although biofouling of acoustic transducers and or other system parts does not always degrade sonar imagery or passive acoustic responses, it can still damage sensitive components over time (Hasselman et al., 2020). For example, if biofouling affects the acoustic system itself and supplementary equipment including cabling, subsurface buoys or surface buoys and batteries (see Figure 10), it can also compromise acoustic release and retrieval mechanisms.

Biofouling can occur within days in some instances (Jha, 2016). Mitigation to reduce biofouling include placing the instruments facing the current, following a regular cleaning schedule and placing in accessible locations. Novel cleaning technologies include test wipers, UV lights, and the use of translucent anti-fouling paint (Hutchison et al., 2020).

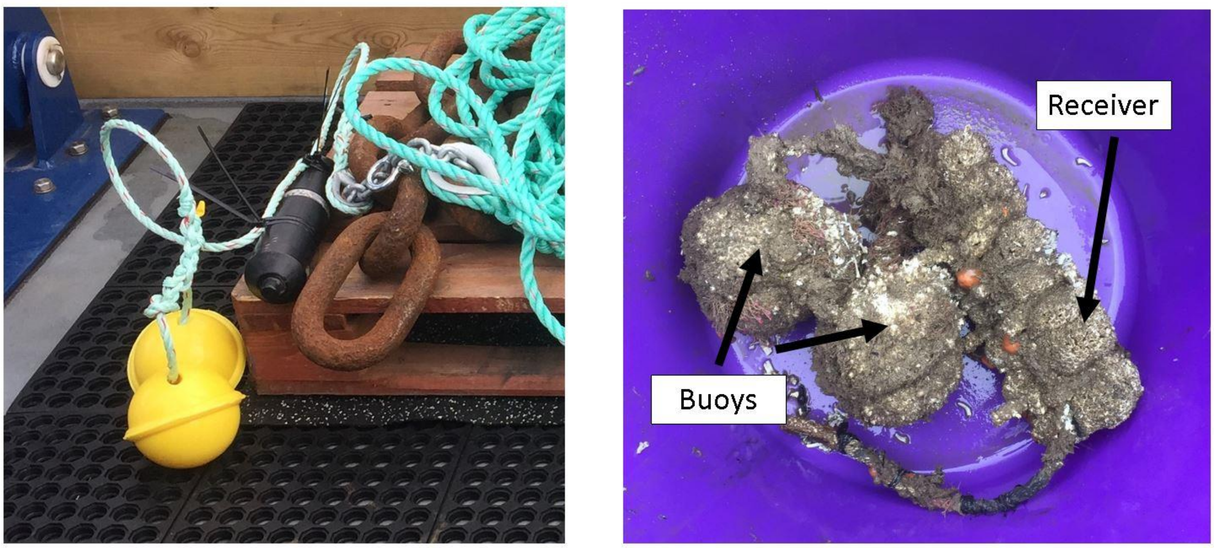

Figure 10. Acoustic tracking receiver and mooring equipment (left); subsurface buoys and receiver after 4 months deployment in the Bristol Channel (right).

8.1.4. Corrosion

In addition to biofouling, the long-term deployment of equipment in seawater may also render it susceptible to corrosion which can be a significant problem. Technology developers advised during this review that there are now well proven and mature technologies in this field to minimise this issue. The use of titanium and aluminium housings, and sacrificial anodes are important measures which are common to much of the equipment used. Despite that understanding we have been advised that the failure of the rotator for the multibeam on the DeltaStream (Ramsay Sound) device may have been due to corrosion, and we understand that corrosion issues compromised multibeam monitoring of the MeyGen site.

8.1.5. Power and data transfer

Selection of power and data recovery methods is an important question for developers when considering monitoring plans. For surface mounted devices and long-term monitoring, cabled power supplies and shore transfer of data are desirable, as they enable real time assessment of data, including identification of problems with the monitoring device, and reduce the requirements for local storage and battery support.

There can, however, be significant potential issues with this approach when applied to seabed mounted monitoring equipment, as evidenced by the FLOWBEC deployment at the MeyGen site, where the power supply was not effectively delivered, and although functional when recovered, the device remained on the sea floor for 18 months without collecting data.

There is therefore a significant trade off to be considered between moored deployments which are easily retrieved and serviced, and deployments fixed to the structure which may be more difficult to recover, however suitable for longer term deployments with power and real time shore links.

8.1.6 Data storage, analysis, and classification

Several of the organisations we spoke with emphasised the importance of having a clear up-front plan for managing data.

As described in section 6, the amount of data produced by techniques such as active acoustics, passive acoustics and high-resolution optical imagery can be exceptionally large; several terabytes of data in a single day for continuous high-resolution optical imagery (Polagye *et al.,* 2014). Although data storage is now relatively cheap, it may still be an issue for remote deployments, limiting deployment times. Even with shore-based data storage the logistical challenge involved in collating, managing, and analysing the information collected can be problematic.

Large data volumes may also limit subsequent analysis, because of the requirement for human intervention to identify and assess events. Real-time analysis for adaptive management can also be labour intensive unless reliable software tools can be used to identify and classify events.

There are various approaches to addressing these problems. Where data can be linked directly to land or vessel-based storage in real time, the problem is minimised because the data storage can be large. This can be achieved through fixed lines, radio link to shore, or satellite link. However, where remote devices are deployed with local storage, alternative techniques are required.

Processing the data in real time, and only storing processed data reduces storage requirements. This approach is built into some COTS tools (C-PODS/F-PODS), and target selection is an option in many acoustic software tools (e.g., those provided by Tritech and PamGuard). Use of these tools is often limited to target acquisition and recording, in some cases using the target data to trigger other instruments.

Data compression and overwriting are also useful tools; Ocean Instruments SoundTrap options have recently been extended to include a device with toothed whale click detection facilities which records .wav files in compressed format. This can be deployed for up to 6 months.

Several researchers and manufacturers are training AI tools to process data to recognise targets using both visual and acoustic data. It is important to recognise current limitations on these techniques; species and site-specific data with known characteristics is required for training. Nevertheless, some success has already been achieved, and AI could be particularly valuable in real time monitoring applications and processing large quantities of visual and acoustic data.

8.2 Suitable monitoring techniques

This section looks at each of the functional requirements and discusses monitoring options, In a Welsh context.

FR1. Presence or absence of a species in a development and the abundance or proportion of key populations of at-risk species in a development.

For both marine mammals and seabirds, presence / absence, and relative abundance can be obtained for both pre and post construction using simple observational techniques. These are inexpensive and reliable. Evidence on marine distribution of these groups is also available, with abundance estimates based on annual, country-wide surveys. Survey protocols should be established for tidal energy developments to standardise collection of baseline and operational data, informed by the approach used for offshore wind.

For cetaceans, quantitative evidence can also be collected by using arrays of fixed COTS PAM units such as C-POD/F-POD and SoundTraps, to collect continuous data covering extended periods including night-time events. These need to be tested with external baseline sound emitters to correct for varying efficiency at different states of tide.

Seal populations are quantified from pup counts using visual surveys of haul-out sites. Tagging studies using DST/satellite tags can provide valuable data for at sea distributions of seals but would be more feasible if also used for other functional requirements (FR2, FR3, FR4) due to labour and costs involved.

For seabirds, tagging techniques using animal-borne data loggers, or high frequency acoustic tags and receiver arrays provide valuable data. Both techniques are costly with the latter unproven for seabirds at this stage. Their deployment for this purpose should therefore only be considered where they are the most appropriate method for other functional requirements (FR2, FR3, FR4).

For fish, the requirements are more challenging. For pelagic commercially exploited species, specialist fishery echosounder surveys are undertaken by International Council for the Exploration of the Sea (ICES) and provide synoptic distributional data as well as stock size estimates. Even for these species, information such as the identity of spawning populations and spawning locations around Wales is incomplete. Surveys also require specialist vessels such as the Celtic Explorer, with electric engines to minimise noise while surveying, and are therefore expensive at ca £20,000 per day.

For migratory diadromous species which are identified as a priority by ORJIP Ocean Energy, information on their riverine distribution is well understood and can be used to infer presence in some cases. - e.g., for tidal range schemes where a river discharges in proximity. However marine distribution of these species remains poorly understood, particularly in the coastal waters of potential RA where tidal range and tidal stream developments are likely to be developed. Capture techniques can be used, and apart from eDNA surveys may be the only practical method to assess life stages for species such as glass eels or juvenile lamprey.

For presence/absence and relative seasonal abundance knowledge gaps could be filled for all RA by a strategic eDNA survey. Acoustic tags could also be used, focussing on sentinel populations of species of concern and combined with receiver arrays deployed in RA. Costs of different techniques are summarised in section 7.

FR2. Occupancy patterns, fine scale distribution and behaviour of mobile species in tidal stream habitats.

For cetaceans, visual observations combined with PAM using COTS monitoring devices deployed in appropriate arrays can provide evidence of occupancy patterns and behaviour (as for FR1). Broad scale information can be obtained from a PAM array with units deployed 500 m apart. Fine scale tracking would require deployment of hydrophone clusters and is only likely to be practical over small areas, such as those immediately around a turbine or tidal range intake. Provided monitoring is corrected for variations in PAM efficiency (e.g., at different tidal states), cetacean behaviour in the areas of interest obtained from PAM can be linked to environmental variables including factors such as tidal state using predictions from tidal models or ADCP data.

Seals and seabirds can also be monitored with visual observations. Where an existing or proposed deployment site is visible from a shore-based vantage point; accurate observations of diving events for individual seabirds or seals can be made using devices such as the

Ornithodolite (Cole, 2019), allowing correlation of geo-referenced underwater space use with environmental data and subsequent inference of behaviour.

Data storage and satellite tags equipped with GPS and sensors also provide valuable data on habitat use and behaviour underwater for both seabirds and seals. Various data storage tags are available (see section 6.8), including both COTS and bespoke, integrated tags. As with marine mammals, observational and tag data can be combined with environmental measurements and hydrographic models to look at high-resolution, spatial-temporal behaviours.

In principle fish can be monitored with optical cameras, fisheries echosounders or multibeam sonars to look at behaviour. Identification of the migratory species of concern is, however, difficult and a reasonable prospect of identifying individual targets is limited to optical cameras at short range in daylight and clear conditions, baited cameras, or high-resolution acoustic cameras such as ARIS. None of these are ideal for this purpose, because of both cost and practicality (range).

For most of the migratory fish species 69kHz acoustic tags combined with acoustic receiver arrays and quantitative scale tagging of key life stages and species in sentinel rivers are therefore the most appropriate techniques. This may require strategic investment.

FR3. Near field interactions including monitoring of avoidance behaviour and collisions. Including frequency, nature, and consequence of near field interactions between mobile species and tidal turbines, evasion responses and rates.

Existing evidence has largely been collected using passive acoustic monitoring (for cetaceans), plus camera and single/multibeam sonars and acoustic tags for fish. We are not aware of any published evidence describing turbine strikes on cetaceans or seabirds, despite quite long monitoring periods at some sites (for example, at MeyGen where PAM systems have been deployed since 2017, with data spanning 2 years). As other authors have pointed out however (ABPmer, 2020) the lack of observations of strikes may reflect the limited range of sites and species observed and constraints on some monitoring schemes because consent conditions have required that the device ceases to operate when marine mammals are in the vicinity.

For cetaceans, visual surveys, PAM arrays (using C-POD/F-POD and/or conventional hydrophones), combined with multibeam/acoustic camera observations (e.g., Tritech Gemini 720 or ARIS 3000) have been shown to be capable of looking at near field interactions. SMRU have used PAM techniques to track harbour porpoise in the immediate vicinity of tidal turbines at MeyGen. Recently published material based on direct observation and tracking of individuals using PAM techniques with bespoke hydrophone arrays mounted on the turbine has shown that proximity and avoidance behaviour can be observed at both medium (10's of meters) and close (meters) range. However positional accuracy declines sharply with distance from the hydrophones when animals are close to the turbines and background noise is high.

Seabird interactions with turbines have been observed using optical cameras around turbines in Bluemull Sound, Orkney. In Welsh waters the value of optical underwater cameras will normally be limited by visibility. Techniques for observing birds in the absence of visibility include direct observation of turbine interactions using multibeam/acoustic cameras or specialist tags with accelerometers (which would identify turbine strikes). Fine scale tracking with high frequency acoustic tags (Lotek JSATS or Innovasea HR) and acoustic receiver arrays could also be considered. Where developers consider that the visibility of the site may be better than the general conditions around Wales, water quality surveys may be appropriate to determine whether optical camera technologies could be used.

For fish, optical cameras, acoustic cameras, and acoustic/radio tagging have been successfully used to look at avoidance behaviour in the vicinity of hydroelectric turbines in a range of freshwater schemes. These have provided evidence of both encounter rates and turbine survival. Evidence in marine situations is limited for diadromous species although there are some observations of marine species, collected using cameras and sonar techniques. These include avoidance behaviour for fish shoals and some collision events with MRE devices have also been reported.

Visual camera techniques around Wales are constrained by low visibility with elevated levels of SPM found around areas of the Welsh coast, particularly the Bristol Channel. Carefully deployed acoustic cameras could provide near field data but the nature of the pictures generated by acoustic techniques combined with limited range and reduced resolution at distance (max range ca 30-50 m) are likely to make identification of species difficult or impossible.

Acoustic tags combined with fine scale tracking arrays can provide accurate data for tagged fish (accuracy better than one metre in 3D). These can be used alongside wider scale tracking methods and used together the techniques can quantify availability and demonstrate both near and far field avoidance. The technique requires the tagged fish to use the area, but if they do not, provided sufficient fish are tagged, this can provide quantitative evidence that risk is low.

Integrated observation platforms carrying mixed packages of monitoring tools have also had success in observing near field interactions. Various research teams have developed integrated observation platforms, such as AMP and FLOWBEC. Although not readily available as COTS tools, these systems may be a preferred option in many situations.

FR4. Behavioural data for different species such as swimming speeds (including burst speeds) and depth utilisation.

Data on swimming speeds and depth utilisation are important parameters for collision risk modelling in EIA. For most species, some data is available in the literature and evidence continues to develop.

For cetaceans, data can be derived from direct observations, including underwater video, PAM, and tagged animals.

For seabirds and seals, underwater video and sensor equipped animal-borne tags can provide this information. Tags can provide depth data energy expenditure and swim speed information.

For fish acoustic tags and sensor equipped acoustic tags which download to acoustic receivers can provide data in the RA. For larger species DST tags may also be used.

FR5. Understanding sensory perception and near field responses to tidal turbines, including the behavioural consequence of noise, to move beyond using audibility as a proxy for behavioural response.

There are a range of ways that marine animals can sense the presence of marine structures, including sight, hearing, sonar, and detection through specialist organs such as lateral lines. Superficially this can be examined by using far and near field monitoring tools such as PAM, tags, and active acoustics to relate behaviour to measured environmental parameters such as noise.

In practice, disentangling the effects of different stimuli and response mechanisms is extremely challenging. Ideally controlled experiments are required, varying single variables. This can, in principle be achieved, e.g., by playing back turbine noise in the absence of physical structures (Hastie et al., 2018). The range of sounds used can extend beyond the known auditory range for the species to identify other receptor mechanisms and impacts. However even these experiments are complicated by the effects of habituation and combined effects (e.g., hearing plus sight).

8.3. Different MRE device types – near field/collision monitoring implications

Section 8.2 identifies the use of PAM, active acoustic devices and tagging techniques as the most efficient methods for collecting near field /collision data in Wales. Device type is of limited relevance to visual survey, tagging and tracking techniques and underwater cameras will have limited value in Welsh waters. Most of this section therefore focuses on the use of PAM and acoustic monitoring for near field interactions. Where monitoring equipment needs to be mounted on or near devices, they are more likely to be affected by noise generated by the energy device.

8.3.1. Surface mounted devices

Aquantis, Sustainable Marine Energy, Magallanes Renewables and Orbital Marine Power all appear to be looking to deploy horizontally oriented turbines mounted on keels or spars below surface vessel(s). Instream energy are looking at a surface mounted hydrokinetic design where the turbine is vertically oriented.

Surface deployments have some significant advantages over seabed-mounted devices for monitoring purposes. Although turbidity is likely to restrict observations around Wales, near surface deployment helps with light penetration, and low-cost cameras may still be useful in some locations to help identify targets when conditions are good. Devices with turbines close to the surface provide potential opportunities to access and service monitoring equipment more easily, as well as simplifying access to power and transmission of data to land.

With advance planning, PAM and acoustic tag receiver clusters, active acoustics or camera equipment may be mounted on the device or flotation units, or on dedicated spars, looking at turbines from close range. These may be fully integrated into the design as bespoke tools or deployed within integrated tools such as the AMP, FLOWBEC or HiCUP. For surface mounted devices this has a major advantage as it ensures that the monitoring equipment remains oriented toward the same point of the MRE device, removing differential relative movement between the two as a problem.

The viability and approach selected will depend on the configuration of the MRE device. Monitoring needs to be considered throughout the design process to ensure that where required, monitoring tools have access to power (ideally battery power recharging from the MRE device), in addition to data storage facilities and control equipment, ideally transmission to shore via high bandwidth radio link, or direct data. If feasible, radio links are likely to be significantly lower costs, but will be limited by distance from shore. Solutions including remote downloads to a manned or unmanned surface vessel might also be considered particularly where array deployments are being considered.

An alternative approach to monitoring surface devices is moored deployment of the monitoring equipment. For near field monitoring using active acoustics or visual cameras, equipment must be deployed close to the turbine, and the relative movement of the monitoring mooring and the device mooring is likely to create significant difficulties. Upward looking seabed mounted deployments may be viable, particularly where water depths are shallow, and range from the monitoring equipment to the turbine is acceptable, though the extensive tidal range around Wales will need to be considered.

There are some disadvantages for surface deployments which also need to be considered when selecting monitoring tools and techniques. The most significant issues are the increased turbulence/noise and movement of the platform because of wave and tidal action. These will affect range and efficiency of both passive and active acoustic devices, as well as making target tracking more difficult.

Surface mounted devices are also less amenable to assessment using mobile vessel based active acoustic survey methods. This equipment must be mounted beneath the survey vessel at a minimum depth and the physical presence of the turbine support structure will also restrict access.

8.3.2. Midwater devices – the Minesto Deep Green tidal kite

The main example of this planned for deployment in Wales is the Minesto ‘kite,’ which has already been deployed in a pilot test off Anglesey. Unlike fixed surface or bottom mounted units, which are fixed in place, monitoring plans for this device must overcome the fact that the device is mobile, occupying different areas at different tidal states (ebb and flood), and moving quite rapidly for most of the time. The speed of movement of the device means that turbulence is high and attaching either passive or active acoustic monitoring equipment to evaluate collisions and avoidance is impractical.

Monitoring requirements in the Minesto marine licence consent focus on marine mammals, and the approach they have adopted is based on the use of PAM, using 2 bespoke hydrophone clusters deployed on the seabed oriented to look at the areas utilised by the tidal kite. The intention of these devices is to locate and track cetaceans which approach the area that the device is operating in. Additional complexity is added by the fact that the location of the device itself, as well as the animal being tracked, is unknown and must be estimated, adding to the potential error in assessing whether a collision or near miss has occurred.

As identified in section 6, this has been a costly deployment, with Minesto estimating equipment costs around £100k, and total costs including deployment, maintenance, and analysis in excess of £250,000 (section 7.5.2.). Although initial deployment has been partially successful in detecting cetaceans, it has not succeeded in tracking behaviour around the device due to issues associated with water ingress and software. Minesto are intending to redeploy the equipment following repairs and upgrades and hope to successfully obtain tracking data in this next deployment.

For other developers intending to undertake similar work, consideration should also be given to the use of existing integrated methods such as the Washington state AMP, FLOWBEC or HiCUP. While the initial equipment costs may appear high, significant amounts of money have been invested in developing these tools, and although they are not yet available as COTS products, many lessons have been learned about the integration, deployment and use of the tools, with successful results in various deployment scenarios. Therefore, although initial costs may appear higher, deployment is more predictable than building a new device.

8.3.3. Seabed mounted devices

Seabed mounted devices are being considered by Nova Innovations, Cambrian Offshore South West Ltd, Verdant Power and Sabella. These devices have the advantage that they are normally at a fixed location, enabling monitoring arrangements to be designed into the scheme. As with surface mounted devices, with advance planning, PAM and acoustic tag receiver clusters, active acoustics or camera equipment may be mounted on the device, looking outward from the turbine, or looking back at the turbine from close range. Again, monitoring needs to be considered throughout the design process to ensure access to power, and if practicable a shore link to recover data in real time and reduce local data storage requirements.

An example of this was the DeltaStream Ramsay sound turbine deployed by Tidal Energy Limited. This had a fixed, powered ‘ramp’ with both passive acoustic clusters and active acoustic monitoring equipment viewing the site from a short distance. This collected some valuable information but also ran into significant difficulties. Only five of 12 hydrophones were fully operational, possibly as a result of damage during deployment, limiting the ability of the device to track cetaceans by this method. Nevertheless, cetacean detections were obtained, and patterns of movement linked to the tidal cycle were observed. The active acoustic element was initially successful, transmitting data to shore, but unfortunately after approximately 5 weeks of operation the rotator became stuck with the active acoustic heads looking away from the turbine, caused by corrosion.

Seabed mounted devices also provide significant challenges for the deployment of monitoring tools. The DeltaStream example described above provides a good illustration of some of the problems. Access to the device is much more difficult than with surface devices, magnifying servicing, repair and data collection issues and costs. While these problems are not insurmountable, they need to be carefully considered at the design stage, for example by including mountings and connectors for devices to land on/attach to. These decisions may be quite significant; underwater dry connection cables, for example, may be more expensive than the monitoring equipment itself.

Remotely deployed monitoring equipment is also worth consideration as it may be more easily accessed and retrieved. Integrated devices or individual devices such as hydrophone clusters, acoustic sonar or camera systems can be deployed on the seabed, near the turbine, and have been successful. Practical issues associated with deployment include locating the device in the correct place, and in the case of devices such as acoustic cameras, ensuring that they look in the correct direction. For that reason, devices with rotator capability which enable the device to be moved to look in the correct direction are preferable.

8.3.4 Tidal range

Tidal range deployments are likely to involve the impoundment within lagoons or estuarine barrages, to create a height and pressure differential which is then used to drive the turbines. There are significant differences when compared with tidal stream devices:

- The impoundment itself might cover a large area, with a range of implications for habitat use, and secondary changes such as changing wave patterns and hydrodynamics in both the near and far field. These issues (and construction impacts) are beyond the scope of this review.
- In addition to turbine collision from passage through the turbines, animals may be subjected to other risks such as predation within the impoundment.
- The turbines will be fitted inside draft tubes which makes monitoring of avoidance behaviour difficult.
- Turbine designs for tidal range are quite different and are more akin to the designs used in river based hydro power schemes. They have higher water velocities through the turbines and hence higher rotation speeds. In addition, there can be a significant pressure differential which can itself cause mortalities for fish species.
- Animals entering the lagoon must exit either via turbines or other structures such as sluices.
- They are likely to be required to have either physical barriers or behavioural deterrents (light / acoustic) built in, which would be expected to deter most marine mammals and have some effect on other species.

Although the potential impacts of these structures and their associated turbines are different from tidal stream devices, in some ways they are more easily monitored. Monitoring of tidal range structures can utilise a range of techniques including direct observation, use of acoustic and visual cameras, together with fine scale tracking using PAM clusters and acoustic fish tagging systems.

The fixed structure of the lagoon, and easy access via land, simplifies visual observations, maintenance, and deployment of monitoring tools. Provided designs account for monitoring requirements at an early stage, PAM, active acoustics and tagging systems can be deployed on fixed structures, with easy access to power and data links.

For all methods, devices may be deployed both on the seaward side of the lagoon wall and inside the impoundment. For fish that will allow individual animals to be identified, enabling passage success and survival to be identified for fish migrating in both directions.

Tidal range projects pose a particular risk to fish. Lagoons may cover a wide area, and when fish encounter the impoundment wall, they may follow along it, increasing the chance of turbine encounters, compared with an open water scheme. In addition, existing tidal range schemes have been built on the coast or in river estuaries increasing the potential risk to diadromous fish, as well as to marine fish which feed in the shallow inshore zone.

For marine mammals, entry into the lagoon is not possible via the turbines, but it is possible that marine mammals could enter via sluices, depending on the design of the lagoon in question. At the Annapolis Tidal Station in Canada a mature humpback whale swam through the sluice gate in 2004 and was trapped in the upper part of the river before finding its way out several days later. On another occasion, in 2007, a body of an immature humpback whale was discovered in the river, and although a post-mortem was inconclusive, it was suggested that the whale may have become trapped in the river after following fish through the sluice gates (see Tethys website for further details).

With respect to birds the risk will depend on the proximity to known nesting or feeding areas and could range from loss or changes to intertidal feeding areas, to risk of collision through entrainment or attraction to turbine structure.

The Swansea Bay Tidal Lagoon Development Consent Order EIA and subsequent Marine Licence application documentation provides a useful example of the issues around consenting and monitoring arising from this type of development.

Monitoring recommendations for Functional Requirements

The functional requirements differ slightly for tidal lagoon as compared with tidal stream. The key functional requirements are FR1 presence/absence and availability, and FR3, specifically far and near field avoidance, turbine impacts and survival. There is an additional requirement to consider subsequent survival for animals that have entered the impoundment, including turbine passage survival as they exit. Monitoring for FR1 and FR2 is the same as for tidal stream developments. For marine mammals, visual observation surveys, combined with a PAM array or tagging for seals, if necessary, will identify presence/absence and abundance as needed. Visual surveys and tags will also cover monitoring requirements for seabirds. For fish, acoustic tagging combined with tracking arrays will provide both presence absence, far field avoidance and quantitative data, as described for Swansea Bay (see section 6.8.3). Identification of sentinel river tagging options for diadromous fish is contained in Clarke *et al* (2021, a, b).

For marine mammals and seabirds FR3 (near field evasion and turbine strikes) and impoundment effects can be addressed using visual observations from the turbine wall, as evidenced by the Annapolis example above, plus the additional use of tags for seabirds if initial visual surveys resulted in concerns. A PAM array and active acoustics could also be considered for marine mammals and seabirds but may be unnecessary and could be included in a secondary monitoring phase if visual observations identified concerns.

For fish, avoidance behaviour and turbine passage success can also be examined using acoustic tags, by deploying an array both within and outside the impoundment. That will provide two-way survival estimates, as well as evidence on residence time within the lagoon or barrage. For species with life stages which may be too small to tag, such as juvenile lamprey, juvenile twaite shad and juvenile eels, trap or netting surveys could be undertaken within the impoundment to determine presence and abundance and extended to intake surveys if these gave cause for concern.

8.3.5 Monitoring system deployment

Mounting arrangements for monitoring tools will depend on the marine energy device being monitored, with varying configurations having been implemented during previous studies of MRE devices (Table A6.1). Deployment of systems on the device itself either looking outward or looking back at the turbine, has the advantage of straightforward access to power and the potential to download data directly to land. This approach was used, among other examples, for the DeltaStream tidal energy device in Ramsey Sound. Alternatively, monitoring tools may be deployed autonomously 30-50 m from the tidal device, observing environmental interactions from that perspective. This has the potential advantage of a clearer view of interactions but may require remote mooring, battery power and increased data storage capacity, unless specific umbilical arrangements are incorporated into the device design. In practice, deployment choices would be affected by whether the marine energy device is mounted in a fixed position on the seabed, moving in the water column (e.g., the Minesto Kite, www.minesto.com) or hanging from a surface vessel where the monitoring equipment can be attached to the vessel looking at the turbine blades.

Assembling monitoring technology on seabed-mounted platforms provides a better best means of observing animal behaviour and interactions with marine renewable energy devices compared to mobile vessel-based deployments (Williamson et al., 2017). The placement, observational window and frequency of recording varies between studies but ultimately results in a trade-off between data resolution and field of data capture. Only instruments (optical or acoustic) with a sufficient range, provide the practical means to investigate the behaviour of marine mammals throughout the entire water column of a typical tidal channel (ABPmer 2020). Examples of seabed platform monitoring positioned away from the tidal stream device include the FLOWBEC sonar platform which combines several instruments to record information at a range of different physical and multi trophic levels for durations of two weeks (Williamson et al., 2016). In addition to this, active acoustic systems have also been mounted on the upstream and downstream sides of a tidal device (e.g. SeaGen, Royal Haskoning 2011).

8.3.6 Access and maintenance

For simpler mobile equipment, designed for long term marine deployment, such as acoustic receivers, C-PODS/F-PODS and SoundTraps, deployments of up to six months are practicable, though because of biofouling, three monthly maintenance is preferable.

Maintenance of equipment is still required to keep it in good working order and is recommended to be undertaken in tandem with any tidal turbine maintenance as a minimum. Communications with equipment developers during this review recommended regular (ideally three monthly) maintenance. Maintenance plans and schedules for monitoring equipment should be included within operational plans at an appropriate frequency.

8.4. Monitoring tidal stream arrays

There is little evidence describing monitoring of arrays or potential MRE array effects. This reflects the current state of development of the industry and limitations on array deployment. The methodologies reviewed in section 6 are those that could be used to assess array deployments.

Potential impacts

As compared with single devices, or groups of two to three devices, two specific concerns arise when considering the main impacts of larger MRE arrays. these are:

- displacement of animals from a large area
- increased rates of collision.

Displacement of animals could suggest they are avoiding the turbine field and hence the risk of collision is reduced. However, for many animals, in particular colonial nesting seabirds where spatial overlap between key foraging hotspots and tidal resource areas exist, displacement can compound negative effects and influence population demographics. This is particularly pertinent for nesting species where foraging range is greatly constrained during chick-rearing and where energetic requirements are at their greatest. Displacement of these individuals reliant on tidal resource areas could lead to a reduction in successful fledgling rate and increased mortality. Careful baseline monitoring before deployment for sensitive colonies should be undertaken to predict and potentially mitigate for such effects.

Increased risks of collision could arise from the fact that animals avoiding one turbine might then immediately encounter another turbine resulting in 'confusion' and a higher likelihood of impact. This may be particularly true for array designs where the turbines are closely spaced, resulting in an increased chance of an animal encountering another turbine immediately after an initial invasion.

Monitoring options - displacement

Initial presence/absence of species in an area can be determined using visual surveys for marine mammals and seabirds and eDNA surveys for fish.

Displacement and area avoidance can be assessed using existing monitoring tools. For marine mammals, a combination of visual surveys, the use of PAM for cetaceans, and tagging methods for seals would provide the necessary data provided area coverage was sufficient. Similarly, for seabirds a combination of visual surveys and tag deployments will be expected to provide appropriate data.

For fish species, visual surveys will not provide useful data. Active acoustic surveys from specialist vessels could provide information on distribution of the major commercial species but might be difficult to undertake within an array field. Acoustic tags and receiver arrays are likely to provide the best way forward for assessing impacts. These have been assessed in some detail (Clarke *et al* 2021a, b), including designs for Welsh waters.

All these approaches would require the collection of pre-deployment baseline data to compare with the post construction operational phase.

Assessing avoidance and collisions

Determining rates of collision is more difficult. In clear water, and daylight conditions optical camera systems could provide the necessary data, but this approach is unlikely to be viable around Wales. Existing technology which could be applied to look at nearfield interactions includes PAM and active acoustics for cetaceans, active acoustics and tags for seals and seabirds, and active acoustics combined with fine scale acoustic tracking (Clarke et al 2021a, b) for fish species. These methods should allow the assessment of movement patterns in the immediate vicinity of groups of turbines, including near field avoidance, although definitively identifying turbine strikes is likely to be at or beyond the limits of existing technologies.

The design of monitoring programmes and the cost of monitoring arrays would need careful consideration. Wider scale studies, to look at far field avoidance and displacement, including pre-deployment surveys could be undertaken as strategic monitoring and research projects, with developer input in specific locations. Near field monitoring using combinations of acoustic, PAM and environmental tools may best be undertaken using integrated packages, either deployed as standalone units or integrated into turbine designs.

For coverage of all species, recognising the significant cost issues, a balanced approach would comprise broad scale PAM and acoustic receivers for fish covering the array area, combined with fine scale tracking arrays / hydrophone clusters and active acoustic monitoring of a subset number of adjacent turbines. The number of turbines monitored would depend on the size of the turbine field and the extent of data previously collected at the site.

In this context, although integration of monitoring into turbine structures is advantageous for long term monitoring, the use of mobile packages may have significant advantage as different groups of turbines could be sequentially assessed, for example to look at differences between groups at the edge of the turbine field and those in the centre.

Consent conditions and adaptive management

Consent conditions for any application will be determined by local circumstances and the details of the development. There are, however, some generic approaches which are worth considering. The use of Adaptive Management for marine developments is a tool that can allow consents to be granted when environmental effects are not well understood. The MRE sector can benefit from this method which can enable deployments with the approach of "learning by doing and adapting as you learn." This will help to reduce scientific uncertainty around the environmental risks by increasing understanding of the effects from a development in place. The process uses available information for decision making and allows management to be adapted once a device is installed based upon monitoring and analysis of outcomes. For example, in Scotland the MeyGen consent is phased, with larger deployments dependent on the results of monitoring of initial deployments. This approach incentivises the developer to undertake the work, and research grants have been provided to support the delivery of the monitoring. This phased approach has been proposed by Morlais, which is currently in determination (see adaptive management, NRW website).

8.5. Technology and other gaps

8.5.1. Hardware / software capabilities

A wide range of hardware types and their capabilities have so far been discussed. There are tools and techniques which can be applied to assess far field distributions, abundance, and behaviour. Near field avoidance can also be assessed, although the techniques required are not COTS approaches and require specialist skills; for example, the use of PAM for actively tracking individual animals, fine scale tracking of fish, and the classification of active acoustic targets, including developing AI tools.

Observing turbine strikes is challenging. While optical cameras can deliver this type of information, they are not suitable for use around Wales because of a lack of underwater visibility. Available techniques are therefore limited to tools, or combinations of tools, such as active acoustics, PAM, and tagging/tracking approaches. Blade sensors have also been trialled with little success. While some of these techniques can provide valuable information on avoidance behaviour, assessing turbine strikes (and associated consequences) is at or beyond the limit of what can be achieved using the equipment which is currently in widespread use.

It may be possible to use high frequency acoustic cameras such as ARIS to observe impacts. ARIS has a short range at these frequencies and consequently a limited ability to visualise more than a small part of the turbine area. This might be partially overcome by linking the camera to a rotator and driving target tracking from other data such as single beam or lower resolution multibeam sonar. ARIS is expensive (ca £80,000 for the unit before integration and deployment costs) and this does not appear to have been trialled to date. 3D acoustic devices such as the Coda Octopus and Echoscope Pipe are interesting and could potentially overcome some of these issues. Coda Octopus claims to enable 3D image tracking of animals around devices such as turbines – i.e., giving a view that can enclose the blades. This has not yet been tested at a tidal energy site, although it has been tested in other situations. The device is expensive with a purchase cost of ca £275,000. As with the ARIS tool these are expensive equipment and initial deployments would be experimental.

Classification of animals

Although the use of passive and active acoustics is sufficiently advanced to enable animals to be tracked in close proximity to a tidal energy device, species identification of the animal is still challenging. Using PAM, most cetacean species can be identified, and when used in combination with active acoustic tracking, it can be used to classify dolphins to species level.

Species recognition of animals from active acoustic data is poor and requires further validation from other monitoring sources. Work is being undertaken by various groups to improve existing species classification software and AI algorithms to assist with the automatic classification of animals, but all such work requires validated animal information (i.e., observation linked to a known species).

Data processing and software

Although there are a range of software tools available to support these techniques, in many cases they are not user friendly and require a high degree of knowledge and expertise to operate. This applies to sonar, PAM (e.g., Pamguard), and to software used to track tagged animals. PAM data analysis becomes even more difficult for 3D tracking of porpoises and dolphins, which is still a relatively new method.

8.5.2 Other gaps / Issues

The review has identified several other issues which we believe are important if monitoring is going to be successfully undertaken in Wales.

Lack of operational sites

The ability to develop new monitoring techniques and validate/improve new techniques is severely constrained in Wales (and in many cases elsewhere) by the lack of operational MRE devices.

People

The technology associated with these programmes, together with the experience required for deployment, means that maintaining a core of capability of highly skilled and experienced staff is necessary to ensure success. In Scotland, a number of co-ordinated interventions have been made to support the sector, and this approach could be considered in Wales. These have included work by Marine Scotland directly with developers, and funding developers (MeyGen) to work directly with SMRU to undertake strategic research as part of their monitoring programme.

Equipment cost

The cost of this equipment is significant, particularly where complex equipment such as integrated monitoring packages, or large arrays of equipment such as CPODS, acoustic receivers, or acoustic tracking clusters are required. In many cases equipment may be required for 2-3 years for specific monitoring programmes but may be capable of multiple deployments across multiple sites (see AMP and FLOWBEC). It may be worth centrally procuring experimental equipment (e.g., AMP device or the Coda Octopus described above) and managing it via an equipment pool, for deployment by researchers working with developers to gather strategically valuable evidence.

Sharing of baseline data / delays

A considerable amount of information exists in various places, including universities in the third sector, which could be used to inform further monitoring protocols. This is not consolidated, and collection may be inconsistent. A particular concern from the MRE sector is that the collection of data such as cetacean or seabird surveys, while feasible and possible at reasonable cost, requires at least two years of data. This can delay completion of EIA and submission of licence applications, delaying projects and incurring additional cost. Strategic surveys of RA could overcome these issues.

Transferability of techniques and results

This is linked to the classification issue identified above. Although researchers have succeeded in some cases in developing classification algorithms which give acceptable results, these are site specific at present. Further work is required to develop classification tools which are transferable.

9. Recommendations

9.1 Recommended monitoring approaches

The most important aspect of this review is the identification of preferred monitoring techniques for use in Wales to monitor impacts of tidal stream and tidal range devices. Table 7 summarises conclusions in this regard. Unless otherwise stated references apply to both tidal stream and tidal range.

Table 7. Recommended approaches to monitoring animal interactions with marine tidal energy devices in Wales assessed for each functional requirement.

Species group	Recommended approaches in Wales	Comments
FR1. Presence or absence of a species around development and the abundance or proportions of at-risk species in the resource area		
Cetaceans	Visual surveys, PAM	Better understanding if used together.
Seals	Visual surveys, Telemetry	GPS/sensor tags with satellite/radio base station/GSM download.
Seabirds	Visual surveys, Telemetry	GPS/sensor tags with recapture/radio base station/GSM download.
Fish	eDNA, Telemetry, capture surveys	eDNA for presence/absence and seasonal relative abundance can be used for other species groups.
FR2. Occupancy patterns, fine scale distribution and behaviour of mobile species in tidal habitats		

Species group	Recommended approaches in Wales	Comments
Cetaceans	Visual surveys, PAM arrays	Needs environmental data/models for comparison with behaviour.
Seals	Visual surveys, Telemetry - integrated tags including accelerometer & magnetometer.	GPS/sensor tags with satellite/base station download. Environmental data (as above).
Seabirds	Visual surveys, Telemetry- integrated tags including accelerometer & magnetometer.	Environmental data needed as above. GPS/sensor tags with base station download or retrieval. Environmental data (as above).
Fish	Telemetry, acoustic arrays + acoustic/sensor tags	Active acoustics could also be considered for some marine species but Species ID not practical for diadromous species.
FR3. Near field interactions including monitoring of avoidance behaviour and collisions. Including frequency, nature, and consequence of near field interactions between mobile species and tidal turbines, evasion responses and rates.		
Cetaceans	PAM, Active acoustics, visual observations + ADCP (integrated tools) Tidal Range: Visual observations and PAM only	Avoidance can be examined using existing technology. Observing turbine strikes is at or beyond the limits of resolution except optical cameras. Consider optical cameras if water at deployment site has good visibility.
Seals	Active Acoustics, visual observations + ADCP (integrated tools) Tidal range: Visual observations only for tidal range + tagging if needed	As above. Need to link visual observations to target tracks to classify targets and develop classification algorithms as no PAM to ID species.
Seabirds	Telemetry, Active acoustics + ADCP (integrated tools) Tidal Range: Visual observations only for tidal range + tagging if needed	As seals.
Fish	Telemetry, Active acoustics + ADCP (integrated tools) Tidal range: Acoustic tagging and tracking, capture surveys	Active acoustics unlikely to ID species; fine scale acoustic tracking preferred. Arrays needed within the impoundment and around turbine intakes and sluices
FR4. Behavioural data for different species such as swimming speeds (including burst speeds) and depth utilisation.		
Cetaceans	Visual observations, PAM	Literature, PAM vertical arrays for depth in Resource Areas.
Seals	Telemetry	GPS/depth sensor satellite or data storage tags.

Species group	Recommended approaches in Wales	Comments
Seabirds	Telemetry-integrated tags including accelerometer & magnetometer, Active acoustics.	GPS/depth sensor data storage tags with download.
Fish	Telemetry, sensor tags	Sensor tags for depth data.
FR5. Understanding sensory perception and near field responses to tidal turbines, including the behavioural consequence of noise, to move beyond using audibility as a proxy for behavioural response.		
Cetaceans	PAM, Active acoustics, Visual	Literature, field observations require environmental data e.g., ADCP. Use of play-back turbine noise.
Seals	Telemetry, Active acoustics, Aerial, Visual	Literature, field observations require environmental data e.g., PAM, ADCP. Use of play-back turbine noise.
Seabirds	Telemetry, Active acoustics, Visual observations	As above.
Fish	Telemetry, Active acoustics	As above.

9.2. Planning and implementation of monitoring programmes

There are several recommendations arising from the discussion:

- For visual and other distribution and abundance surveys, such as eDNA, protocols should be established for tidal energy developments to provide baseline and operational data, informed as appropriate by those used for offshore wind. This should be standardised across the sector.

- Monitoring strategies may need to include both far and near field elements. Where monitoring is required, early consideration should be given to determine whether the monitoring device should be moored or part of the turbine structure.

- Where integration with the turbine structure is the preferred option, monitoring approaches should be planned from the early design stages of the device and incorporate monitoring requirements such as location, power, and data links.

- Maintenance plans and schedules for monitoring equipment should be included within operational plans at an appropriate frequency.

- Data management and analysis plans should be put in place before monitoring starts.

9.3. Strategic interventions

Based on our conclusions above, the following strategic interventions could be considered and would provide considerable assistance to the tidal energy sector:

Baseline monitoring

These proposals aim to provide data that developers can rely on for initial assessments, covering presence / absence, relative seasonal abundance, and in some cases abundance or the proportion of populations present.

- A baseline visual observation programme for seabirds and cetaceans covering the resource areas; and run for two years pre-construction could be considered. This would include visual surveys for both mammals and seabirds.

- A strategic eDNA sampling programme for fish (and potentially all species), to create a common baseline data set benefiting all developers, again ideally run over a two-year period.

- The establishment of acoustic tracking arrays, together with sentinel tagging studies to provide better understanding of migration patterns for diadromous fish around the Welsh coast. (see Clarke *et al*., 2021a for detail).

Testing innovative technologies

Several innovative technologies exist which could be trialled to establish their effectiveness in monitoring near field encounters, including turbine strikes. Consideration could be given to supporting emerging technologies such as development of 3D acoustics, ARIS, and fine scale acoustic movement studies using high resolution equipment for tracking of fish, seabirds, and seals.

Developing and maintaining expertise and equipment

Building capabilities in the development and operation of monitoring technology, and the subsequent analysis of environmental data to develop a centre of excellence in Wales, would facilitate research and development which addresses fundamental knowledge gaps that developers must address to obtain consent for MRE projects. This should be collaborative and cross disciplinary, including, amongst other experts: biologists, engineers, computer scientists, and statisticians. This will ensure Wales has a strong platform to develop and grow within this emerging industry and would allow knowledge and lessons learnt to be widely shared for the benefit of the MRE sector. This could follow the approach taken in Scotland, where a similar function is provided by Marine Scotland and SMRU.

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11. Annexes

Annex 1. Organisational contacts

List of organisations that have been contacted either through questionnaire or online meeting which have been included in this report. Multiple entries show we spoke to a number of different people within the same organisation but who held distinct positions, their names are removed for the purpose of confidentiality.

Table A1.1. List of organisational contacts.

Organisation / Sector	Sector
Government Agency	
Natural England	GOVERNMENT AGENCY
Natural Resources Wales (SNCB for Welsh Inshore waters)	GOVERNMENT AGENCY
Natural Resources Wales (SNCB for Welsh Inshore waters)	GOVERNMENT AGENCY
Marine Energy Wales	NGO
Irish Marine Institute	State agency
Developers	
Cambrian Offshore South West Ltd.	MRE DEVELOPER
Minesto	MRE DEVELOPER
Environmental groups	
Atlantic Salmon Trust	NGO
Game and Wildlife Conservation Trust	NGO
British Trust for Ornithology	NGO
Royal Society for the Protection of Birds (Cymru)	NGO
Royal Society for the Protection of Birds	NGO
Wildlife Trust of South and West Wales	NGO
Sea Trust - survey in high energy sites (Strumble and Ramsey Sound)	NGO
WDCS - annual surveys of Risso's off Bardsey	NGO
Academia	
Sea Mammal Research Unit	ACADEMIA / CONSULTANT
Sea Mammal Research Unit	ACADEMIA / CONSULTANT
Bangor University (Oceanography)	ACADEMIA
Bangor University	ACADEMIA
NGO / Consultancy	
Marine Energy Engineering Centre of Excellence	NGO
ORE catapul / Ven associates	NGO / CONSULTANT
ORE catapul	NGO
ORE catapul	NGO
Offshore Renewables Joint Industry Programme for Ocean Energy	NGO / CONSULTANT

xodus	Consultant
xodus	Consultant
xodus	Consultant
Equipment manufacturers	
Chelonia C-POD/F-POD PAM manufacturer	MANUFACTURER
BioSonics (sonar developer)	MANUFACTURER
BioSonics (sonar developer)	MANUFACTURER
Vanishing Point Marine / Towed array hydrophone developer	MANUFACTURER
RS Aqua	MANUFACTURER
Tritech Gemini	MANUFACTURER
Sound metrics ARIS / DIDSON	MANUFACTURER
Teledyne Marine	MANUFACTURER
Coda Octopus	MANUFACTURER
Innovasea (VEMCO)	MANUFACTURER
Thelma biotel	MANUFACTURER
Lotek	MANUFACTURER
Sonotronics	MANUFACTURER

Annex 2. Modelling tools and parameter requirements

Three model types are currently used to estimate the number of animals (marine mammals and seabirds) likely to collide with underwater turbines:

- The Encounter Rate Model (ERM)
- The Collision Risk Model (CRM)
- The Exposure Time Population Model (ETPM)

These models are simple in their concept and were initially applied to open horizontal axis turbines (Scottish Natural Heritage 2016). However, recent research has adapted these models for use with non-horizontal axis turbine designs including tidal kites (Schmitt et al., 2017).

The ERM is based on a predator-prey model initially developed for modelling jellyfish preying on plankton (Gerritsen & Strickler 1977). The CRM is based on the ‘Band Model’ developed to estimate risk of collision of flying birds with wind turbines (Band et al., 2007).

The approaches of the ERM and CRM are broadly similar in that they both use a physical model of the rotor and the body size and swimming activity of the animal to estimate the potential collision rate (ABPmer 2020). The ERM model focuses on the volume per unit time swept by each blade, while the CRM focuses on the number of animal transits through a rotating rotor and the collision risk during each transit. The ETPM uses population modelling to assess critical additional mortality due to collisions which would cause an adverse effect on an animal population. The model translates that into the collision rate for each animal within the volume swept by the rotors which would be sufficient to cause such an effect (Scottish Natural Heritage 2016).

Table A2.1 provides a review of the parameters used for the various models used in research around marine energy devices. These include both operational parameters and species-specific data.

Operational parameters for the model are site specific. Data such as turbine diameter, number of blades and rotation speed should be readily available to include in the model. Site specific characteristics such as tidal flow speeds, water depth and device depth should also be included, and again are easy to obtain (Scottish Natural Heritage 2014).

Biological data for CRM for marine mammals are:

- Body length
- Body width
- Population density
- Depth distribution
- Number of animals in the population at issue

Seabird data required for CRMs include:

- Dive depth, duration and frequency.
- Distance travelled during dives and the underwater space occupied.
- Swim speed (ascent, descent, horizontal and burst/escape).
- Underwater manoeuvrability, awareness and evasive response (avoidance).
- Activity levels in relation to the annual cycle, tidal state and time of day.

Collecting robust data for these parameters is challenging with many models using the same values as taken from flight data.

Fish data required include:

- Population density
- Swim speed - mean and burst speed.
- Body length
- Body width
- Preferred swim level
- Behavioural traits - e.g., seasonal migration, diel behaviours, schooling, avoidance

Table A2.1. Modelling parameters used for collision and encounter risk modelling.

Title	Subject	Parameters	Methods	Results / Limitations	Reference
CRM					
Development of collision risk assessment tool	Space crafts	n/a	n/a	n/a	Alarcón-Rodrigues et *al.*, 2003 R2
Maximum collision probability considering variable size, shape, and orientation of covariance ellipse.	Orbiting objects	n/a	Maximum collision probability analysis	n/a	Bai et al., 2016 R4
A tool for simulating collision probabilities of animals with marine renewable energy devices https://doi.org/10.1371/journal.pone.0188780	Marine animals – tidal kite (Minesto)	• animal length (L) • animal velocity (v) • the animal's initial position (z, y) • a phase lag (δ) between animal and kite motion • the time it takes the kite to fly the entire track (T) • the mean kite depth (D) • the water depth (H)	freeCAD (general purpose computer aided design framework allows users to create and manipulate geometric objects via python or GUI) For area swept by blade: $P_A = \frac{NColl}{NSim}$ *NSim* - the number of all simulations *NColl* - the total number of collisions	See reference for detail. Ecological data such as depth distributions and transit rates could be multiplied with the collision probability distribution to progress towards a more realistic estimate for collision risk. Lack of knowledge on actual probability distributions for a certain species to occur in a given time or space and the reaction in the vicinity of a	Schmitt et al., 2017

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		• the height (h) and width (w) of the figure of eight describing the kite trajectory	$P_{SweptA} = \frac{NColl}{NCollPos}$ *NCollPos* - the number of positions at which at least one collision occurred for all delays tested (a function of MRE device configuration). Varying time step convergence	device are larger sources of error than the expected variations in collision probability due to design or operation of the MRE device.	
Refining estimates of collision risk for harbour seals and tidal turbines -Review of models for harbour seals https://data.marine.gov.scot/dataset/refining-estimates-collision-risk-harbour-seals-and-tidal-turbines	Seals (harbour/common)	• The local population density, D; • The effective cross-sectional area A of approaching blades (the 'predator'), taking account of the effective radius of the animals ('the prey') if animals are to clear the blades; and • The mean speed of the turbine blades relative to the animal, V. Specifically: • B = number of rotors. • b = number of blades. • w = width of a turbine blade. • R = turbine blade length.	C_{ERM}=DxBb(w+2r)(R+r)xv(1+($u^2/3v^2$))	Lack of empirical data on evasions and avoidance so all models assume no avoidance or evasion. Only uses horizontal approach in model. More detailed tidal currents needed.	Band et al., 2016 R5

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		• r = ‘effective radius’ which is the clearance required (from the centre of mass) due to the body size of the animal. • v = blade speed relative to the water which combines tangential speed and • current speed (the blade speed is assumed to be faster than the animal • speed relative to the water current, in this case); and • u = animal’s swim speed relative to the water.			
Collision risks between marine renewable energy devices and mammals, fish and diving birds http://nora.nerc.ac.uk/id/eprint/504110/	Marine mammals, fish and diving birds	• body length • Animal radius = Ra • population • area of sea • density =D • water depth at turbine = H • depth distribution of animal	Encounter Rate Model adapted to collision risk model. C = Z.(1-Pa). (1-Pe) C= collision rate Z=encounter rate P_a =probability of avoidance P_e =probability of evasion	Assumes independent movement of turbine and animal. Lack of behavioural metrics (avoidance, evasion). Density estimate is lacking (simplified).	Wilson et al., 2007 R92

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		• probability of being within turbine depth horizon = P • depth of turbine • rotor diameter • Blade width = W • Blade length = Rb • proportion per m depth • mean swimming speed = ua • mean rotor speed versus water = ub • encounter radius = R	Encounter model based on predator-prey encounters. $D=P.2.R_b/H$ $Z = A. (u_a^2 + 3\ u_b{}^2) / 3u_b .D$ $R_a = 2L/\pi^2$ $A = (W + R_a).(R_b + R_a).N$		
A probabilistic Model for Hydrokinetic Turbine Collision Risks: Exploring impacts on fish https://doi.org/10.1371/journal.pone.0084141	Fish	• Fish activity • Rotor swept area • Population size • Assessment unit (time) • Detection distance • Current speed • Rotor radius • Fish burst speed	CRM based on fault tree analysis (within the field of probabilistic risk assessment). Many aspects for each model step: Population estimated to pass through turbine area - Array passage P_p ; probability of entry into hazardous part of turbine P_t ; probability of co-occurrence of fish passing when turbine in operation P_o ; avoidance failure P_a ; probability of being swept by current into	Minimal risk for small-sized fish, higher probability of collision risk to larger fish of turbines (≥5m). Lack of data for model validation. Variability between species (size, shoaling/solitary etc.)	Hammar et al., 2015 R31

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		• No. of blades • Rotational speed • Angle of attack • Fish length	hazardous zone P_z ; turbine injury, P_i ; caused by hydraulic stress (P_s), such as pressure drop and shear, or collision (P_c) with a rotor blade; and probability of blade incident (P_b). Collision will only occur if close-range evasion failure, P_e; Lastly, blade damage (P_d) determines the probability of a collision to be severe.		
An agent-based model to predict fish collisions with tidal stream turbines. https://doi.org/10.1016/j.renene.2019.11.127	Fish	Biological • Swim speeds • Body length • Body width • Vertical migration • Navigation (migration) • Preferred swim level Turbine • Xyz position • Orientation • Diameter • No. of blades	CRM created using numerical agent-based models (ABM) of fish movement to include predictions of collisions.	Turbine collision rates predicted to be low (<1.1%)	Rossington & Benson 2020 R68

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		• Rotor depth • Max blade width • Blade pitch • Min. operating velocity • Max RPM • Tip speed ratio (TSR) • Spin direction			
Collision risk modelling for tidal energy devices: A flexible simulation-based approach https://doi.org/10.1016/j.jenvman.2020.111484	Marine animal (theoretical 'seal') and Minesto style kite and tether	Ecological • Speed (linear velocity, 2 x speeds, mean swim speed of adult harbour seal, and fast speed to represent a seal travelling in fast flowing tidal stream) • Size (ellipsoid shape to simulate adult and pup seal shape) • Angle of approach (yaw and pitch; downstream travel, flat and 45° angle downward trajectory) • Start point • Time lag	Simulation based freeCAD (general purpose computer aided design framework allows users to create and manipulate geometric objects via python or GUI) (see Schmidtt et al., 2017). Many simulations run to calculate collision risk probability. Refinements of probabilities made by post-processing results to integrated data from animal dive profiles (U-shaped)	Highest chance of collision for 'adult' seal on downward trajectory at slow speed (CP=0.214). Lowest chance for 'pup' at fast speed on downward trajectory (CP=0.037). Highest collision probabilities at static base of device. Can use actual profile data in model. No information on animals' distribution in water column.	Horne et al., 2021 R40

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		Kite device (see Schmitt et al, (2017) for formulas.		Uniform distribution and dive profiles reduce CR on flat trajectories.	
Assessing collision risk between underwater turbines and marine animals SNH report including basic ERM/CRM and ETPM models for developers to use. https://tethys.pnnl.gov/publications/assessing-collision-risk-between-underwater-turbines-marine-wildlife		ERM: • D is the 'prey animal' density, per m3 • B is number of rotors • b is no of blades • w is the width of a turbine blade, as viewed from the side • R is the length of a turbine blade • r is the 'effective radius' – the clearance required due to the body size of the prey animal • v is the blade speed relative to the water, combining tangential speed and current speed • u is the prey animal's swim speed relative to the water CRM: • D animal density	ERM based on model developed by Wilson et al. (2007). Considers the volume swept by the turbine blade and the no. animals present. CERM=D*Bb(w+2r)(R+r)*v(1+(u2/3 v2)) CRM based on Band et al. (2000; 2007; 2012) from models of birds and wind farms adapted to marine env. Collision rate: CCRM = D * B π (R+0.5W)2 * v * pcoll No of transits = D B π (R + 0.5W)2v No of collisions = No of transits x Risk of collision during a single transit	Same issues as Band et al (2016) and Wilson et al. (2007) above.	SNH 2016 R71

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		• Cross-sectional area of B rotors • V is animal speed • Mean risk of collision during single transit • r is the radius from the rotor centre at the point of transit • b is no of blades • Ω is rotational speed • v is speed of animal relative to rotor (taken as the mean current speed) • c is the chord width of the blade at radius r • γ is the pitch angle of the blade at radius r, relative to the rotor plane • L is the length of the animal • W is its breadth (wingspan for a bird) • $\alpha = v/r\Omega$ ETPM: • t is the time period under study	Collision risk of a single transit at centre radius: $p(r) = (b\Omega/2\pi v)$ [$\|\pm c \sin\gamma + \alpha c \cos\gamma\| + \max(L, W\alpha)$] (see report for further details). EPTM (Exposure Time Population Model): Developed from Grant, Trinder & Harding (2014). $C_{ETPM} = N * T * \alpha / t$		

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		• C_{ETPM} is the collision rate, in collisions per second, during that time period • N is the number of animals in the population at issue, for example the animals within a particular breeding colony. • T is the 'exposure time', i.e., the total time within the period for which each animal is exposed to risk (i.e., the time it spends within the volume swept by rotors), assuming no avoidance • α is the collision rate – the number of collisions per unit time - for each animal exposed to risk			
Estimating the probability of fish encountering a marine hydrokinetic device	Fish, marine hydro-kinetic device (MHK)	Parameters taken from echoview software, from echosounder data. • Month • Diel condition • Tide stage	Encounter probability model based on probability of fish being at device-depth when was absent; probability of fish behaviour changing in response to device in far-field; probability of fish being at device-depth in near-field when device present.	Modelled maximum probability of fish encountering the whole device was 0.432 and encountering the device foils was 0.058.	Shen et al., 2016 R72

Title	Subject	Parameters	Methods	Results / Limitations	Reference
https://doi.org/10.1016/j.renene.2016.06.026			Bayesian Generalized Linear Model (BGLM) used to estimate probability of fish being at certain depths.	Differences in probabilities based on month, diel and tidal stage. Mobile hydroacoustics indicated that fish likely avoided the device with horizontal movement beginning 140 m away.	
Brims Tidal Array Collision Risk Modelling - Atlantic Salmon https://tethys.pnnl.gov/publications/brims-tidal-array-collision-risk-modelling-atlantic-salmon	Atlantic Salmon	• Min Clearance between blade tip and sea surface at LAT • Water /channel depth (m) • Number of rotors • Rotor diameter (c/f) • Rotor radius • Number of blades • Maximum blade width • Blade pitch at blade tip • Blade profile • Rotation speed • % time not operational • Mean current speed	Not detailed, although Brand (2015) is referenced, not directly for model method though.	Avoidance behaviour of salmon unknown Assuming 95% avoidance, up to 32 salmon (1SW + MSW) and 211 smolts would potentially collide with the maximum development scenario of 200 turbines (Scenario 4) per year, as highlighted by the cells shaded in the table.	Xodus Group, 2016

Title	Subject	Parameters	Methods	Results / Limitations	Reference
		• Channel width			
Applying a simple model for estimating the likelihood of collision of marine mammals with tidal turbines https://marineenergyjournal.org/imej/article/view/21/4	Marine mammals (Harbour porpoise, Harbour seal, Killer whale), bladed turbine based on a reference model tidal turbine,	$n_{turbines}$ = the number of turbines in the channel A_{rotor} = the swept area of the rotor $A_{channel}$ = the area of the channel P_{rotor} = probability of animal entering the rotor-swept area. rpm = the rotations per minute of the turbine. t_{swim} = the time it takes the marine mammal to swim through the turbine swept area; and n_{blades} = the number of blades on the turbine.	Simplified CRM devised. $P_{rotor}=n_{turbines} * A_{rotor}/A_{channe}*P_{depth}$ The proximity of the marine mammal to the turbine is assigned a binary outcome (0 or 1) for the probability of being present in the rotor-swept area, and for encountering the blade. A probability distribution was created based on the swept area of each of the three blade sections. $A_{tip}=\pi r^2-\pi(2/3*r)^2$ Based on the rate of blade rotation, the probability of the marine mammal encountering the blade (P_{enc}) is calculated by determining the area that the blade would sweep in the time it takes for the animal to pass through the swept area: $P_{enc} = rpm * t_{swim} * n_{blades}$	CRM results indicate risk of being seriously injured from a collision with a tidal turbine to range from 0.035% for harbour seals in Lashy Sound (UK) to 0.006% for HP and 0.011 for KW in deeper wider channel sites. Supports evidence so far that collision between a tidal turbine blade is a rare event even when behavioural (avoidance) data is not included. Does not address overall risk to populations.	Copping and Grear, 2018

Title	Subject	Parameters	Methods	Results / Limitations	Reference
Improvements to Probabilistic Tidal Turbine-Fish Interaction Model Parameters (pnnl.gov)	Fish (sturgeon)	• Probability of Blade Rotation • Distribution of Water Velocity over the Tidal Cycle • Fish Distribution • Turbine Rotor Area • Blade Interaction with Fish • Fish Distribution • Avoidance Behaviour	$P_{Strike} = \sum_{V_W=0}^{V_{W,Max}} P1 \cdot P2 \cdot P3 \cdot P4 \cdot P5 \cdot P6 \cdot P7$	Model was updated with data collected for model parameters including P3: Fish Distribution (East vs. West Channel), P5: Blade Interaction with Fish and P6: Fish Distribution Initial model estimated collision risk to be less than 0.1% (PStrike = 0.086%), and updated model found collision risk to actually be lower (PStrike = 0.032%)	Tomichek et al., 2015

Annex 3. MRE global device list

Table A3.1. List of global MRE devices either historically or currently installed or in planning. Devices coloured red indicates the device is either not currently installed or little monitoring information is available, green highlights that the device is either installed or has been installed and information on monitoring is available, blue highlights test sites.

Device	Developer	Project Site	Location	Technology	Status	Notes
Australia						
Tenax Energy	Tenax Energy	Clarence Strait Tidal Energy Project	Clarence Strait	Array, test site	Array. 456MW. Planned Project	
Atlantis Resources	Atlantis Resources	San Remo Test Site	San Remo, Victoria	100 kW Aquanator™ device, a 150 kW AN-150™ (Nereus™ I) device, and a 400 kW AN-400™ (Nereus™ II) device	Subscale. 2006-2015. device no longer in the water	Development stated site poses no threat to migrating mammals from an acoustics perspective nor any of the local population of seals and penguins due to the low rpm of the turbine when in operation.
Canada						
Annapolis Tidal Station	Nova Scotia Power Corporation		Bay of Fundy and Annapolis River	Tidal barrage	Single turbine in barrage. 20MW. 1984-Shutdown in 2019	Little information on fish displacement. A mature humpback whale swam through sluice gate in 2004, survived. An immature humpback whale found dead in 2007, post-mortem inconclusive but suggested whale had become trapped in the river after following fish through sluice gate. (link to further information on Tethys website)
Fundy Ocean Research Center for	Fundy Ocean Research	FORCE	Bay of Fundy	Test Site	Test Site. 2.0-22MW. In Operation	Environmental Effects Monitoring Program (EEMP)

Device	Developer	Project Site	Location	Technology	Status	Notes
Energy (FORCE) Test Site	Center for Energy (FORCE)					Fundy Advanced Sensor Technology (FAST) Program
Clean Current	Ovintiv (formerly EnCana Corporation) / Clean Current Power Systems	Race Rocks Tidal Energy Project	Race Rocks Ecological Reserve, British Columbia	Clean Current bi-directional ducted horizontal axis turbine	Subscale, single device. 0.065MW. 2006-2011. device no longer in the water	Baseline surveys- towed underwater video (SIMS-Subtidal Imagery and Mapping System) and diving / Oystercatcher nests mapped. Little post-monitoring as concluded turbine turns slowly (10-20 rpm) so was minimal risk to animal collisions.
Atlantis Resources	Atlantis Operations Canada Ltd. (a joint venture of Atlantis Resources Ltd. and Rio Fundo Ltd. (a DP Energy affiliate))	FORCE	Minas Passage, Bay of Fundy, (FORCE)	Atlantis Resources AR1500 Three No.1.5 MW three 18 m blade turbines	4.5MW.	FORCE undertakes monitoring reporting annually and reports on their environmental effects. http://fundyforce.ca/environment/monitoring/
OpenHydro	Cape Sharp Tidal (OpenHydro and Emera)	FORCE	Minas Passage, Bay of Fundy, (FORCE)	Open centred 2 MW turbine (16 m diameter)	2MW. unknown	
Andrtiz Hammerfest Hydro	DP Energy Ltd.	FORCE			unknown	
PLAT-I	Sustainable Marine Energy		Grand Passage, Nova Scotia	The PLAT-I energy converter,	Single device. 0.28MW. 2018-2019. Ongoing project	Various monitoring taking place; collision; mammals, fish.

Device	Developer	Project Site	Location	Technology	Status	Notes
	(SME) / SCHOTTEL HYDRO GmbH			SCHOTTEL Hydro SIT250 tidal turbines		
Chile						
Marine Energy Research and Innovation Centre (MERIC)	Chilean Ministry of Energy, CORFO, Enel Green Power, Naval Energies		Chile	Mixed research	Research Facility on-going. VTB facility from 10 kW to 500kW (from 2019 onwards).	Yes, multiple research areas.
China						
BaiShakou Tidal Power Station	People's Republic of China		Shandong Peninsula	Tidal lagoon	array, lagoon. 0.960MW. 1978-unknown	Unavailable
Haishan Tidal Power Plant	Government of China		Maoyan Island, Zhejiang Province	linked basins plant	Single device. 0.25MW. 1975-In Operation	Unknown
Jiangxia Pilot Tidal Power Plant	China Guodian Corporation		Yueqing Bay, Wenling	Tidal range power plant	Single device. 4.1MW. 1980-In Operation	
Wanxiang-I Project	Harbin Engineering University		Guishan Channel	Floating, moored, vertical axis turbine.	Subscale. 0.07MW. 2002-2004. device no longer in the water	
Wanxiang-II Project	Harbin Engineering University		Zhejiang province	bottom fixed vertical-axis tidal current energy plant	single device. 0.04M. 2005-2006. device no longer in the water	
England, UK						

Device	Developer	Project Site	Location	Technology	Status	Notes
Multiple (Test site)	Perpetuus Energy Limited / Isle of Wight Council	Perpetuus Tidal Energy Centre (PTEC)	St Catherine's Point, Isle of Wight	Test Site	Test Site. 30MW. On Hold	
PLAT-0	Sustainable Marine Energy Ltd. (SME)		Off Yarmouth, IOW. Then EMEC.	Test Site	Test Site.	Operational monitoring occurred at IOW and also continued at EMEC. See EMEC, for monitoring at that location.
France						
La Rance Tidal Barrage	Électricité de France (EDF)		Rance River near Saint Malo, Britany	Tidal range power plant	Single device. 240MW. 1966-In Operation	
Sabella	Sabella		Fromveur Passage, off the coast of Ushant Island, Brittany	Sabella D10 turbine Horizontal Axis Tidal Turbines (HATT)	Single device. 1MW. 2015-In Operation	One hydrophone (HTI-99-HF) with data recorded on acoustic recorder (SDA14) on the device mooring structure. 2 x C-Pods during initial installation from November 2015 – July 2016. Recorded data from before turbine was operational in addition to when turbine was operational. 1 C-POD installed on the camera tripod next to the rotor.) https://www.etipocean.eu/assets/Uploads/2017-08-29-ETIP-Ocean-webinar-Minimising-negative-environmental-impacts.pdf
Ireland						
Multiple (Test site)	Irish Marine Institute, Sustainable Energy Authority of Ireland (SEAI)	SmartBay	Galway Bay	Mixed	Test Site. 2006-Ongoing test area	Subsea test and monitoring platform. Marine mammal monitoring to assess the effect of a ¼ scale ocean energy device on harbour porpoise presence was carried out in Galway Bay between 2009 and 2010 when an ocean energy scaled device was on site (O'Brien et al., 2012; O'Brien, 2013). Monitoring was also carried out at

Device	Developer	Project Site	Location	Technology	Status	Notes
						2 control sites, one 1km east of the test site and the second was 500m west of the test site.
Multiple (Test site)	Sustainable Energy Authority of Ireland (SEAI)	Atlantic Marine Energy Test Site	Annagh Head, west of Belmullet	Mixed	Test Site. Fully consented in 2015. Yet to have device in place.	EIA undertaken. No device put into operation, therefore no post operational monitoring.
Italy						
Ponte di Archimede SpA - Kobold turbine	Ponte di Archimede SpA	Enermar Project	Strait of Messina, along the Sicilian coast	The Kobold turbine (cross flow rotor, 6m in diameter, equipped with three blades with a span of 5m)	Single device. 0.05M. 2001-2005. device no longer in the water	
Fri-El Green Power SpA - Seapower system	FRI-EL Green Power SpA - ADG	Messina Project	Strait of Messina, Sicilian Coast	Floating turbine	Subscale array. 0.006MW, 0.020MW, (0.5MW planned). 2007-2011. device no longer in the water	
Seapower GEMSTAR System	Seapower scrl		Strait of Messina	Midwater turbine	Subscale. 0.3MW. Planned Project	
Japan						
IHI Ocean Current Turbine	IHI Corporation		Kagoshima Prefecture	Midwater turbine	Single device. 0.1MW. In Operation	
Netherlands						
Tocardo Tidal Power T2 turbines	Tocardo Tidal Power	Oosterschelde Tidal Power project	Eastern Scheldt storm surge barrier	five T2 turbines	Array. 1.25MW. 2015-In Operation	https://tethys.pnnl.gov/publications/monitoring-getijdenturbines-oosterscheldekering-jaarrapportage-2018

Device	Developer	Project Site	Location	Technology	Status	Notes
Northern Ireland, UK						
SeaGen	Marine Current Turbines (MCT) - now SIMEC Atlantis Energy	Stangford Lough	Strangford Lough, Northern Ireland	SeaGen twin turbine system	single device. 1.2MW. 2008-2016. decommissioned 2019	https://tethys.pnnl.gov/publications/seagen-environmental-monitoring-programme-final-report
Deep Green Tidal Kite DG500	Minesto	Stangford Lough	Strangford Lough, Northern Ireland	Deep Green 500 midwater tidal kite.	R&D testing	Optimising multiple multibeam sonars to assess marine life interactions with an underwater kite (Lieber et al., 2017)
DP Energy Ltd.	Fair Head Tidal Energy project	Fair Head Tidal Energy project	Fair Head, North Antrim, Northern Ireland	Array, test site	Array. 100MW. Planned Project	
SubHub Community Demonstrator	QED Naval Limited	QUB tidal test site	Castle Ward Bay in Strangford Narrows, Northern Ireland	The SubHub Community Demonstrator (SH-CD) is the smallest version in the Subhub range that supports up to three sub-100 kW turbines to provide a total power output between 150 – 300 kW.	Single device. 0.150-0.3MW. 2019-Trials on-going	
Norway						

Device	Developer	Project Site	Location	Technology	Status	Notes
Andritz Hydro HS300	Andritz Hydro	Hammerfest Strøm tidal project	Kvalsund in Finnmark county	HS300 horizontal axis turbine	Subscale, single device. 0.3MW. 2003-2011. device no longer in the water	Observational surveys undertaken.
MORILD II Tidal Power Plant	STRAUM		Gimsoy stream, Lofoten,	Floating, moored turbine (x4)	Array. 1.5MW. 2010-2012. device no longer in the water	
Portugal						
Ocean Flow Energy Evopod	Ocean Flow Energy	SCORE (SuperComputing Online Re-planning Environment) Project-Sustainability of using Ria Formosa Currents on Renewable Energy Production	Faro-Olhão Inlet, Ria Formosa	OceanFlow Energy - Evopod E1 (1:10th scale prototype)	Single device, subscale. 0.001MW. 2017-2017. device no longer in the water	Baseline surveys - SCUBA, ROV video transects, visual census (mammals, birds, fish), hydrophones (background noise)
Scotland, UK						
EMEC Fall of Warness Grid-Connected Tidal Test Site	European Marine Energy Centre (EMEC)	EMEC	orkney Islands, Scotland	TEST SITE	Test Site. 4.5-10MW. 2005-In Operation	http://www.emec.org.uk/services/consents/
EMEC Shapinsay Sound Non-Grid-Connected	European Marine Energy Centre (EMEC)	EMEC	Shapinsay Sound, Orkney, Scotland	Test Site	Test Site. Non-grid connected. In Operation	http://www.emec.org.uk/facilities/scale-test-sites/

Device	Developer	Project Site	Location	Technology	Status	Notes
Nursery Tidal Test Site						
QED Naval and HydroWing	QED Naval and HydroWing (previously Tocardo Tidal Power)	EMEC (InToTidal)	Fall of Warness, Orkney	BlueTEC floating platform with a Tocardo T2 tidal turbine	Single device. 0.275-1.375MW. 2017-2020. on hold	EMEC environmental monitoring
Voith HyTide 1000	Voith Hydro	EMEC	Fall of Warness, Orkney	1MW horizontal axis turbine HyTide 100	Single device. 1MW. 2013-2015. device no longer in the water	Underwater video Visual obs.
Atlantis Resources AK-1000	SIMEC Atlantis Energy	EMEC	Fall of Warness, Orkney	Atlantis AK-1000, twin horizontal turbine blades on single device	Single device. 1MW. 2011-2019. Device no longer in the water	Marine Mammal Observation (MMO) https://tethys.pnnl.gov/publications/european-marine-energy-centre-emec-decommissioning-programme
Orbital Marine Power SR2000	Orbital Marine Power	EMEC	Fall of Warness, Orkney	2MW SR2000	Single device. 2MW. 2016-2018. device no longer in the water	Six Vivotek colour cameras were installed to provide underwater footage of the SR2000. Accelerometers were installed in the blade tips with the intention of detecting any abnormalities in blade speed that could be attributed to collision events. Strain gauges were also installed in the blades for collision detection.
Andritz Hydro Hammerfest HS1000	Andritz Hydro	EMEC	Fall of Warness, Orkney	HS1000 device is a fully submerged, bottom mounted, rotor, variable pitch turbine.	Single device. 1MW. 2011-2015. device no longer in the water	Nacelle mounted video camera strain gauges mounted on blades. MMO present when vessel in area Acoustic monitoring effects on wildlife Displacement monitoring using EMEC's wildlife observation data. http://tethys.pnnl.gov/annex-iv-sites/emec-fall-warness-grid-connected-tidal-test-site

Device	Developer	Project Site	Location	Technology	Status	Notes
Nautricity CoRMaT tidal stream turbine	Nautricity	EMEC	Fall of Warness, Orkney	CorMaT turbine	Single device. 0.5MW. 2017 - Device taken out in 2018. Project ongoing	https://www2.gov.scot/Resource/0051/00518157.pdf
Atlantis Resources AR2000 turbines	SIMEC Atlantis Energy	Sound of Islay Demonstration Tidal Array	Sound of Islay, Scotland	AR2000 turbines, 24m rotor diameter horizontal turbine	Array. 10MW. Planned Project	https://www.scottishpowerrenewables.com/userfiles/file/Sound%20of%20Isaly%20Demonstration%20Tidal%20Array%20Cable%20Route%20Environmental%20Report_May%202013.pdf
Nautricity CoRMaT tidal stream turbine	Nautricity	Argyll Tidal Demonstrator Project	Mull of Kintyre, Scotland	CorMaT turbine	Single device. 0.5MW. Never installed. Device installed at EMEC. see above.	
DEME Blue Energy (DBE)	DEME Blue Energy (DBE)	West Islay Tidal Project	Rinns of Islay, Islay, Inner Hebrides, Scotland	Mixed	Array. 30MW. Planned project.	
DP Energy Ltd.	DP Energy Ltd.	Westray South Tidal Project	Westray Firth, Eday, Egilsay and Rousay, Scotland	Horizontal Axis Tidal Turbines (HATT)	Array. 200MW. Planned project.	
Stingray tidal generator	The Engineering Business	Yell Sound	Shetland, Scotland	Stingray tidal generator	Single device. 0.15MW. 2002-2003. device no longer in the water	
Argyll Tidal Demonstrator Project	Argyll Tidal Limited (ATL)		Mull of Kintyre, Argyll and Bute, Scotland	Mixed	Array. 0.5MW. Planned Project	
OpenHydro	Brims Tidal Array Ltd. / OpenHydro		South Walls, Hoy, Orkney	Test Site	Array. 200MW. on hold	
Atlantis Resources	MeyGen Tidal Energy	MeyGen	Pentland Firth, Scotland	Atlantis Resources	Array. 6-86MR. 2016 - In Operation	On-site monitoring via SCADA (Supervisory Control and Data Acquisition)

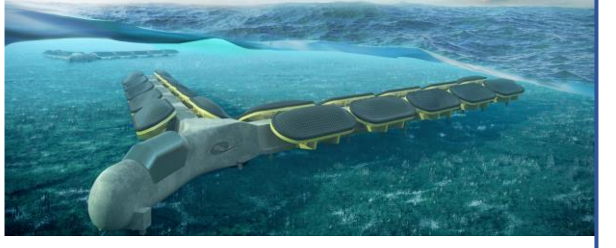
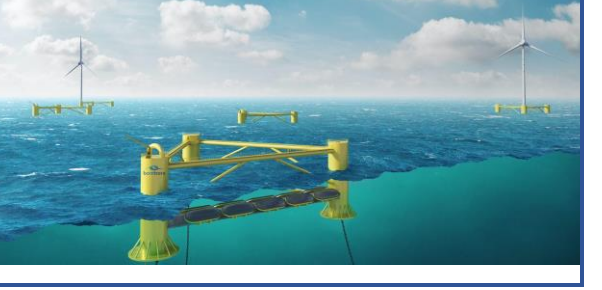
Device	Developer	Project Site	Location	Technology	Status	Notes
Limited: AR1500 Andritz Hydro Hammerfest: HS1500	Project - Phase I			Limited: AR1500 / Andritz Hydro Hammerfest: HS1500		FLOWBEC
Nova Innovation M100 turbine	Nova Innovation	Shetland Tidal Array	Bluemull Sound, Shetland	3x M100 turbines	Array. 0.3MW. 2016- In Operation	Underwater video monitoring and collision modelling
South Korea						
Sihwa Tidal Power Plant	Korean Water Resource Corporation		Sihwa embankment	Barrage turbines	Array. 254MW. In Operation	https://tethys.pnnl.gov/publications/environmental-ecological-effects-lake-shihwa-reclamation-project-south-korea-review
Uldolmok Tidal Power Station	South Korean Government		Uldolmok Strait in the Yellow Sea, at Jindo Island, South Jeolla	crossflow Helical Turbine	Single device. 1-50MW. 2009 in operation	No
Sweden						
Uppsala University - river vertical axis turbine with five blades	Uppsala University	Söderfors Project	Söderfors, River Dal, Uppsala.	vertical axis turbine	Single Device. 0.0075MW. 2013 in operation	Yes, Salmon released, Sonar system track salmon.
Wales, UK						
Deep Green Tidal Kite DG500	Minesto	Holyhead deep	Holyhead, Wales	Deep Green 500 tidal kite	0.5MW-80MW. 2018. In Operation	hydrophone array See ES.
Deltastream	Tidal Energy Ltd	Ramsey Sound	Ramsey Sound, Pembrokeshire, Wales	400 kW device of 3-	Single device. 0.4MW. 2016-2016. Device failure and	Environmental monitoring information available. Meeting had with Cambrian Offshore South West Ltd.

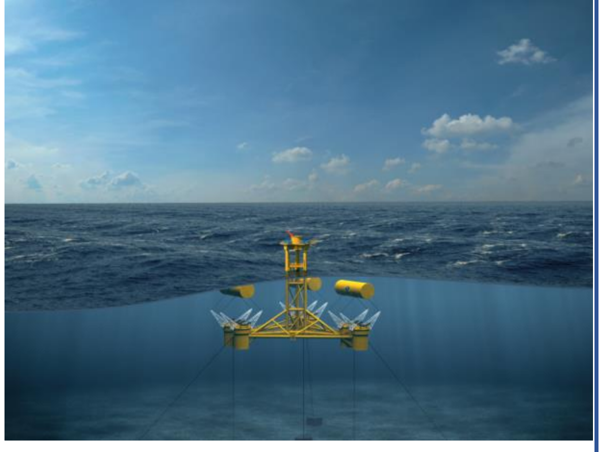
Device	Developer	Project Site	Location	Technology	Status	Notes
				bladed turbines	company no longer exists. Device still in water. Cambrian Offshore South West Ltd has received investment to regenerate the site.	
Swansea Tidal Lagoon (SBTL)	Tidal Lagoon Power / Andritz Hydro		Swansea, Wales	Tidal Range Lagoon	Array of turbines in Lagoon wall. 320MW. On Hold	
Multiple (Test site)	Morlais	West Anglesey Demonstration Zone	Off Holyhead, Anglesey Wales	TEST SITE	Test Site. Pre consent phase	EIA undertaken.
USA						
Ocean Renewable Power Company (ORPC) - TidGen® Power System	Ocean Renewable Power Company (ORPC)	Cobscook Bay Tidal Energy Project	Maine	TidGen™ Power System, advanced design crossflow (ADCF) turbines	Single device. 0.75MW. 2012-2017. device no longer in the water	Acoustic monitoring, benthic & biofouling monitoring, fisheries and marine life interaction, hydraulic monitoring, marine mammal monitoring, bird monitoring
Verdant Power Gen4 turbine	Verdant Power	Roosevelt Island Tidal Energy (RITE) Project Demonstration	East River, New York	six Gen4 KHPS turbines	Array. 0.175MW. 2006-2008. Device no longer in the water	Collision - Paired DIDSON and split-beam echosounder on vessel for obs. During operation Hydrophones - noise 24 split-beam transducers (SBT) Bird Observations - shoreline obs.
Verdant Power Gen5 turbine	Verdant Power	Roosevelt Island Tidal Energy (RITE) Project Pilot	East River, New York	Gen5 turbines	Array. 1.05MW. 2012 - In operation. In October 2020 three Gen5 Free Flow System Turbines were installed.	RITE Monitoring of Environmental Effects (RMEE)

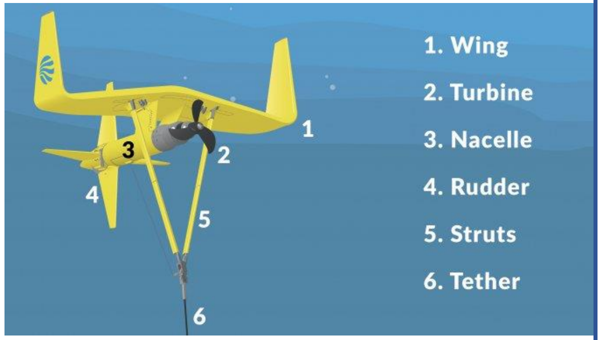
Device	Developer	Project Site	Location	Technology	Status	Notes
Ocean Renewable Power Company (ORPC)	Ocean Renewable Power Company (ORPC)	Western Passage Tidal Energy Project	Eastport, Maine	Bottom-Mounted	Array. 5MW. Planned Project	

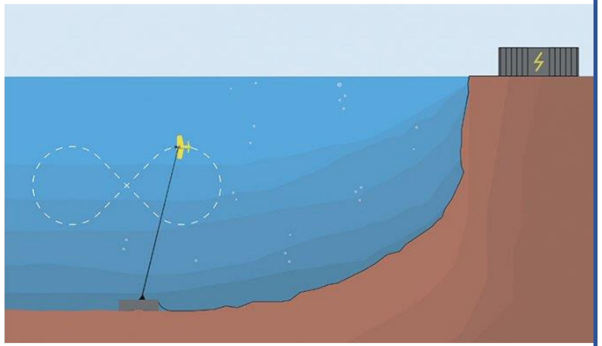
Annex 4. Designs of devices which could potentially be deployed in Wales.

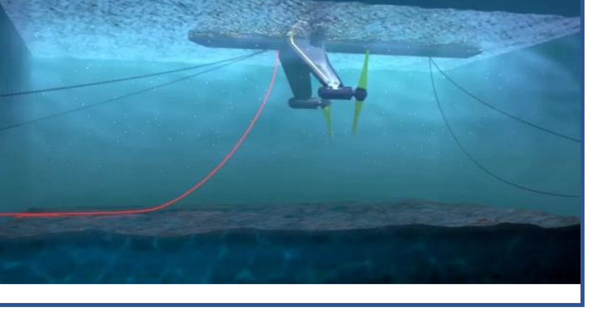
Table A4.1. List of devices and designs which could potentially be installed in Wales.

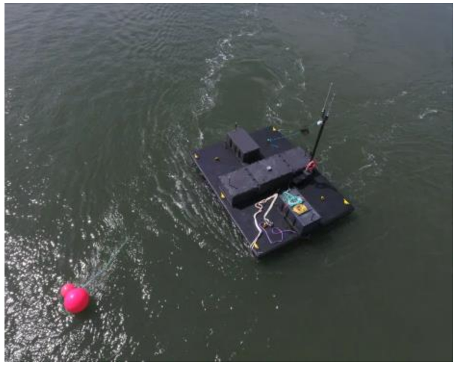
Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Bombora	Wave	mWave™ wave energy converter	planned 2021	1.5MW	Pembrokeshire	 

Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Marine Power Systems	wave	WaveSub	N/A	4.5-10MW	FaB Test in Cornwall	
	Wind	WindSub	N/A	10-15MW	N/A	

Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Marine Power Systems	Wave and wind	DualSub	N/A	15-20MW	N/A	
Minesto	Tidal stream, Tidal Kite	0.5MW Deep Green Tidal Kite	2018 & 2019	0.5MW (increasing to 10MW)	Holyhead Deep, Angelsey, Wales, UK.	

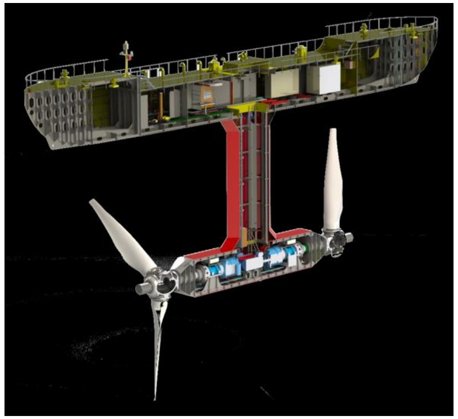
Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Minesto	Tidal stream, Tidal Kite	0.5MW Deep Green Tidal Kite	2018 & 2019	0.5MW (increasing to 10MW)	Holyhead Deep, Angelsey, Wales, UK.	
Nova Innovation	Tidal stream	100KW seabed turbine	N/A	0.5MW (x5 100KW turbines)	Bardsey sound & Morlais demonstration zone	

Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Orbital marine power	Tidal stream	O2 2MW floating tidal turbine.	N/A	2MW	Morlais demonstration Zone, Angelsey	 

Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Verdant Power	Tidal stream	Gen5 seabed turbine	Aiming for 2022-23	30MW by 2025-26	Morlais demonstration Zone, Angelsey	
BigMoon	Tidal stream	Kinetic Keel	N/A	N/A	Morlais demonstration Zone, Angelsey	

Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Sabella	Tidal stream	seabed horizontal-axis technology turbine	N/A	N/A	Morlais demonstration Zone, Angelsey	
Instream Energy Systems	Tidal stream	Floating array - Vertical axis hydrokinetic turbines (VAHTs)	N/A	1MW	Morlais demonstration Zone, Angelsey	

Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
HydroQuest	Tidal stream	N/A	N/A	N/A	Morlais demonstration zone, Angelsey.	
Aquantis	Tidal stream	Floating turbine	N/A	N/A	Morlais demonstration zone, Angelsey.	

Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Sustainable Marine Energy	Tidal stream	PLAT-O, PLAT-I. Floating and midwater tidal turbine.	N/A	N/A	Morlais demonstration zone, Angelsey.	
Magallanes renovables	Tidal stream	Floating turbine	N/A	N/A	Morlais demonstration zone, Angelsey.	

Developer	Technology	Turbine make / model.	Installation date	Power capacity (MW)	Location	Device design
Cambrian Offshore South West Ltd. (TIGER project) **www.interregtiger.com www.ore.catapult.org.uk/stories/tiger** **Formally TEL Delta stream project.**	Tidal stream	Seabed tidal turbine	N/A	N/A	Ramsey sound	

Annex 5. eDNA survey - additional information on approach and analysis

A5.1. Sampling strategies and equipment

Effective sampling strategies and laboratory practices are a key element of eDNA studies. All that is required is a water sample representative of the location. However, the sensitivity of the techniques requires stringent methods to avoid cross contamination between samples, sample replication and positive/negative control samples. Good training of sampling staff is also important. Once collected, properly preserved samples can be used for a wide range of purposes. For example, samples taken from resource areas can be used to identify the presence of cetaceans, seabirds and fish.

Various sampling strategies can be used with varying degrees of simplicity or sophistication.

At the simplest end of the spectrum, water samples can be obtained using simple, sterile, water bottles (Miskin bottles or similar). These samples can be transported to the laboratory to be filtered or may be filtered on site/aboard ship with portable filtering equipment (Ratcliffe et al., 2020). This approach has the benefit of simplicity, but sample volumes are limited, and the sample is instantaneous, so limited to a single point in time. To cover a larger area and time period effectively, the study will require a higher number of samples.

At the most complex, surface buoys have been fitted with sampling equipment which undertakes the analysis *in situ* (Jens Carllson, pers com). This reduces the use of expensive ship time and ensures consistency of sample timing, but the length of deployments is limited by the capacity of the buoy to carry reagents, and the necessity of filter changes. The equipment is also costly and with longer deployments there is risk of equipment loss and damage.

Recently, Natural England have successfully trialled an automated sampler which takes large volume samples over one or more tidal cycles (Mynott & Marsh, 2020). Samplers are submerged for ~24 hours, with the ability to filter ~50 L of water over this period. The pilot study looked at 6 sampling locations along the South Coast of England between October 2019 and February 2020. Effectively, this provides an integrated sample across the tidal cycle, covering a large area (i.e., the area over which the tide has passed during the period in question). They then applied a metabarcoding approach to their samples and identified 74 fish species, some of which had not been previously recorded in the area, including a number of the species of relevance to this review such as Allis and Twaite shad, eels and Atlantic salmon. In addition, this study investigated temporal variation across the sampling period and haplotype diversity (which can be used to look at gene flow between metapopulations).

Figures A5.1 and A5.2, courtesy of Applied Genomics, use the AVS Dev Tide Modelling Tool to illustrate the area coverage which can be obtained by deployment of 6 samplers on spring and neap tides, respectively. For each of the modelled tidal excursion areas, the area in yellow indicates water movement at the sea surface and the area in green indicates water movement at 1 metre above the benthos, where the sampler water inlet is assumed to be placed.

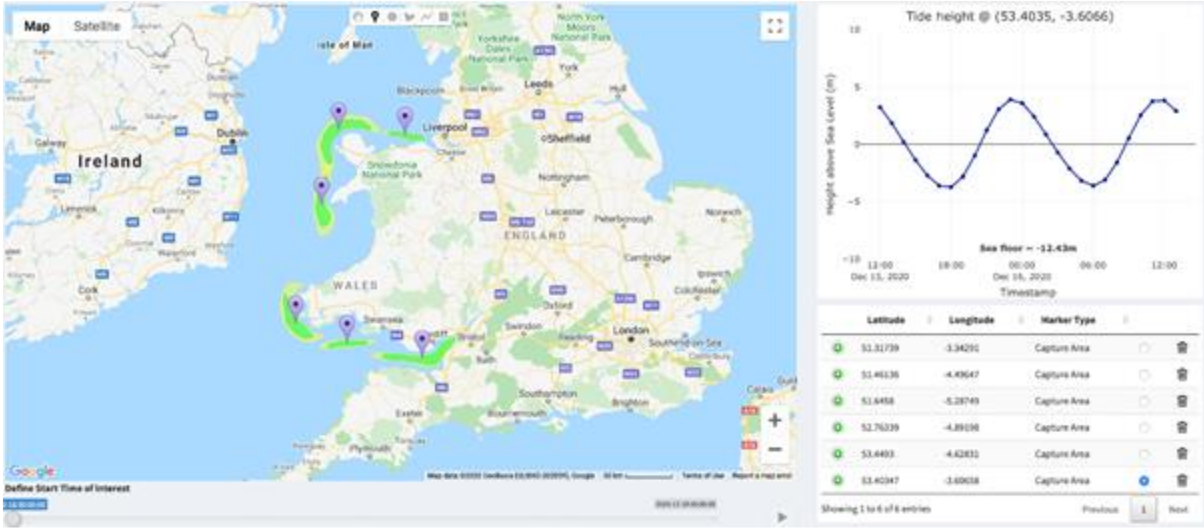


Figure A5.1. Indicative sample areas on Spring tides (modelled using data from 15th December 2020).

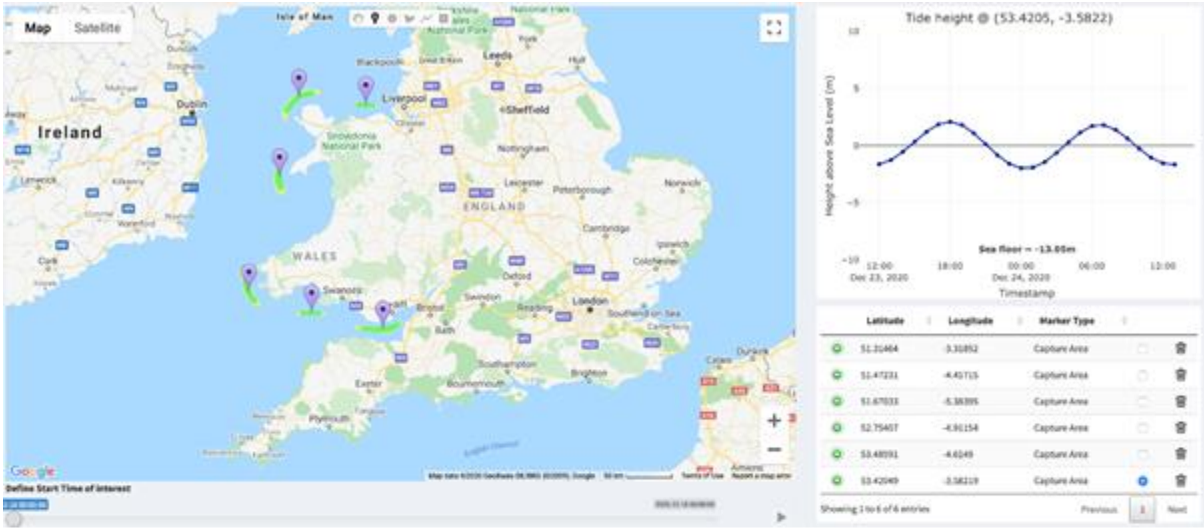


Figure A5.2. Indicative sample areas on Neap tides (modelled using data from 23rd December 2020).

A5.2 Analytical techniques

There are two main techniques used in eDNA studies, Sanger sequencing, and metabarcoding, or next generation sequencing (NGS). All techniques have strengths and weaknesses (Harper et al., 2018; Holman et al., 2019).

PCR, or qPCR, is the amplification and quantification of genetic material (DNA) using targeted primers (oligos) specifically designed to detect the target species. Following PCR, DNA amplicons must undergo sequencing to be identified. Sanger sequencing provides more sensitivity for a target species, and a longer, more specific resulting sequence. However, this approach can only look at one group, or a small number of species at one time. For example, if the sample DNA is from an environment (eDNA), rather than a tissue sample, it is likely that it contains many fish species, therefore it would be useful to use species specific primers to pick out the desired species.

Metabarcoding, or NGS, amplifies whole or partial regions of a gene, giving a full list of species present from the chosen gene region. For example, the fish specific 12S-V5 primers will amplify the 12S variable region 5, and identify several species of fish (Miya et al., 2020). Primers can be chosen to enable us to look at all species of interest. It can, however, be less sensitive Sanger sequencing in that it produces shorter, more variable, reference sequences.

Both methods can be compared with existing genetic sequence databases such as the National Center for Biotechnology Information (NCBI) to identify the species present, and species will only be identified if they are included in reference databases (Bohmann et al., 2014). In practice, provided that both the samples, and resulting eluted DNA are stored with appropriate controls in place, samples can be used for both qPCR and metabarcoding, and can be re-used in future as new techniques and primers develop. Metabarcoding can therefore be used to identify the broad range of species present in a group, with qPCR analysis undertaken to target species of particular interest (Ratcliffe et al., 2020)

Annex 6. List of equipment types used at tidal energy sites.

A6.1 Summary of PAM used at MRE sites.

Table A6.1. Summary of deployment locations, passive acoustic measurement (PAM) equipment configurations employed, acoustic measurement type. Table taken from SOS report (Hasselman et al.,2020).

Location	Methodology used	Objectives	References
Lynmouth, UK	Drifting boat hydrophone	Operational noise	(Parvin et al. 2005; Maunsell Faber and METOC 2007; Richards et al. 2007)
Strangford Lough, UK	Drifting boat hydrophone	Operational noise	(Nedwell and Brooker 2008; Gotz et al. 2011; Keenan et al. 2011)
Fall of Warness, Orkney, UK	Drifting boat hydrophone Drifting buoy hydrophone	Background, Construction and Operational noise	(Aquatera 2010; Beharie and Side 2011; Wilson et al. 2011, 2014)
Cobscook Bay, Maine, USA	Drifting buoy with pair of vertically separated hydrophones	Operational noise	(CBTEP 2012)
Kvalsund, Western Finnmark, Norway	Drifting boat hydrophone	Operational noise	(Akvaplan-niva 2009)
East River, New York, USA	Towed hydrophones	Operational noise	(Ocean Energy Systems 2013)
Admiralty Inlet, Puget Sound, USA	Bottom mounted hydrophone Drifting buoy with vertical pair of hydrophones Drifting boat hydrophone Drifting vertical line array	Background and Operational noise. Planned transmissions	(Bassett 2010; Polagye et al. 2012; Xu et al. 2012; Bassett et al. 2013, 2014; Copping et al. 2013)
Minas Passage, Bay of Fundy, Canada	Drifting buoy hydrophone Bottom moored system Turbine mounted system Moored subsurface float Boat deployed horizontal array	Background noise. Free-spinning turbine noise.	(Martin and Vallarta 2012; Tollit and Redden 2013; Martin et al. 2018; Auvinen and Barclay 2019)
Schottel, Queen's University Belfast Tidal Test Site in Portaferry, Northern Ireland	Drifting buoy hydrophone	Background and Operational noise, including free-pinning and braking	(Schmitt et al. 2015)
River Turbine, Iguigig, Alaska, USA	Drifting spar buoy hydrophone	Operational noise	(Polagye and Murphy 2015)
Site Expérimental Estuarien National pour l'Essai et l'Optimisation	Drifting boat hydrophone	Background, Installation and Operational noise	(Giry et al. 2018)

Hydrolienne (SEENOH), Bordeaux, France			
Cook Inlet, Alaska, USA	Moored directional array Moored hydrophone	Background noise Beluga whale monitoring	(Worthington 2014)
Ramsey Sound, UK	Boat deployed partial drifting hydrophone with subsurface float and weight 12 element turbine mounted array	Background noise Cetacean detection and localization	(Broudic et al. 2012a, 2012b; Willis et al. 2013; Malinka et al. 2018)
Grand Passage, Canada	Bottom moored hydrophone Drifting buoy hydrophone Turbine mounted hydrophone	Background noise Planned transmissions	(Malinka et al. 2015; Wilson and Martin 2019)
West Scotland (Sound of Islay, Scarba, the Great Race, Gulf of Corryvreckan, Kyle Rhea, the Sound of Sleat)	Moored C-PODs Drifting C-PODs Moored vertical line array Bottom mounted hydrophone Towed hydrophone array Drifting hydrophone	Porpoise detection and localisation. Baseline, Construction and Operational noise	(Harland 2013; Wilson et al. 2013; Benjamins et al. 2016, 2017; Macaulay et al. 2017)
Mississippi River, Memphis, Tennessee, USA	Moored hydrophone Drifting hydrophone	Background noise Operational noise	(Bevelhimer et al. 2016b)
Sequim Bay, Washington, USA	Bottom mounted vector instrument array	Test tones	(Raghukumar et al. 2019)
MeyGen demonstration array, Scotland	High frequency 12 hydrophone array mounted on turbine support structure	Marine mammal localisation and tracking	(Gillespie et al. 2020)

A6.2 Common imaging sonars for marine monitoring.

Table A6.2. Summary of the six most used imaging sonars for monitoring marine renewable energy devices with general specifications Table taken from SOS report (Hasselman et al.,2020).

Sonar	Frequency (kHz)	Field of view (°)	Range (m)	I/O trigger	SDK	Applications
Tritech Gemini	720	120 x 20	<120	Yes	Yes	Vessel surveys, SeaGen, AMP
Teledyne BlueView	900/2250	130 x 20	<100/<10	Yes	Yes	AMP, vessel surveys
Kongsberg Mesotech	500	120 x 3, 7, 15, 30	<150	Yes	No	AMP, vessel surveys
Blueprint Subsea Oculus	i) 375 ii) 750/1200 iii) 1200/2100	i) 130 x 20 ii) 70 x 12 iii) 60 x 12	i) <10 ii) <120/<40 iii) <30/<10	Yes	Yes	Vessel surveys
Imagenex Delta T	260	120 x 10	<150	Yes	Yes	FLOWBEC
Sound Metrics Aris	i) 1200/700 ii) 1800/1100 iii) 3000/1800	i) 28 x 14 ii 28 x 14 iii) 30 x 15	i) <80/<35 ii) <35/<15 iii) <15/<5	No	No	ORPC, Verdant RITE

A6.3. Availability of optical cameras

Table A6.3. Standard types of optical cameras and related components available to conduct nearshore fisheries and marine mammal related observations studies. Table taken from Hasselman et al. (2020).

Camera Type	Application	Cost (US$)	Benefits / Limitations
Action Cameras	Nearshore, short term recording.	300 - 800	Small size, flexible recording, low cost.
Low End Monochrome	Mid-high definition, long term	1,000	Low cost, low light sensitivity.
High End HD	High definition, long term.	5,000	Species ID
High End HD Optical Zoom	High definition, long term.	7,000	Variable and close-up viewing region.
IP Cat 5	Mid-high definition, long term.	3,000 - 6,000	Extended cable length.
COTS (digital still)	High resolution, colour enhancements.	500 - 1,000	Waterproof housing needed, small size, flexible recording.
Machine Vision Video (CMOS/CCD)	Variable framerate, small size, low power requirement, Flexible interfaces (fire wire, USB, GigE, IP) variable control for camera recording parameters, can select a specific ROI.	Variable	Waterproof housing needed, temperature range, cable length for high frame rate systems.
Accessories			
LED Sea Lighting	Nocturnal viewing	1,500	24-hour observations,
Laser and Housing	Close range scaling/sizing	1,000	Fish/object sizing,
Pan and Tilt	Increased viewing area	3,000 - 4,000	Sector viewing,
Linear Motion Rail	Predetermined sector viewing.	5,000	Increase observation region, programmable.
Motion trigger mechanisms	Enabling camera when marine animal comes into frame of view	1,000	Enables use of camera and compilation of video data only when target is detected, decreasing data storage and analysis costs.
UV lights, copper rings, wipers	Decrease biofouling around optical instruments.	1,000 - 2,000	Deters and slows growth of biofouling organisms that decrease quality and obscures optical images.