Review of potential collision between tidal stream devices and marine animals

Report No: 444

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Mae gwrthdrawiadau posibl rhwng anifeiliaid y môr a dyfeisiau llif llanw yn bryder o ran trwyddedu defnydd o'r fath oherwydd ansicrwydd presennol. Comisiynodd Cyfoeth Naturiol Cymru ABPmer i gasglu ac adolygu unrhyw ddata sydd ar gael a gasglwyd oddi wrth ddyfeisiau yn y fan a'r lle, a'r llenyddiaeth ehangach, a ymchwiliodd i wrthdrawiadau rhwng mamaliaid y môr, adar môr a physgod a dyfeisiau llif llanw. Ar sail canlyniadau'r adolygiad hwn, darperir argymhellion ar y bylchau allweddol sy'n parhau yn y dystiolaeth ac sydd angen eu llenwi er mwyn cefnogi'r gwaith o gydsynio ac asesu datblygiadau o fewn y sector hwn yng Nghymru ymhellach.

Roedd y dull o fynd ati i gynnal yr adolygiad tystiolaeth hwn yn cynnwys tair tasg allweddol. Roedd Tasg 1 yn gofyn am nodi'r holl brosiectau llif llanw a gynlluniwyd ac a weithredwyd yn fyd-eang a dod i benderfyniad ynglŷn â'u prosesau o ran asesu a monitro gwrthdrawiadau posibl. O hyn, dewiswyd is-set o 21 o ddyfeisiau/datblygwyr/prosiectau llif llanw a oedd wedi monitro neu asesu'r risg gwrthdrawiad er mwyn llywio'r adolygiad tystiolaeth hwn.

Roedd Tasg 2 yn gofyn am sefydlu templed safonol i gasglu manylion monitro ac asesu gwrthdrawiadau ar gyfer pob un o'r prosiectau llif llanw a ddewiswyd. Nod hyn oedd sicrhau bod y dystiolaeth wedi'i chasglu mewn modd cyson, a bod yr holl ganlyniadau wedi'u darparu ar daenlen ar wahân. Darparwyd taenlen hefyd yn cynnwys amrediad eang o lenyddiaeth yn ymwneud â gwrthdrawiadau posibl rhwng anifeiliaid morol a dyfeisiau llif llanw, dulliau monitro, datganiadau amgylcheddol, modelu risg gwrthdrawiadau, ac unrhyw lenyddiaeth berthnasol arall.

Roedd Tasg 3 yn gofyn am gasglu data monitro a gwybodaeth o'r datblygiadau/dyfeisiau llif llanw a ddewiswyd, o nifer o ffynonellau, gan gynnwys trafodaethau â datblygwyr ac academyddion llif llanw, yn ogystal ag adolygu asesiadau amgylcheddol, adroddiadau monitro, a’r llenyddiaeth ehangach o ymchwil a adolygwyd gan gymheiriaid ac adolygiadau strategol. Wedyn, adolygwyd y wybodaeth hon er mwyn penderfynu: dulliau presennol o fonitro gwrthdrawiadau posibl rhwng dyfeisiau llif llanw a phob un o'r tri grŵp derbynnydd ar gyfer anifeiliaid morol (mamaliaid morol, adar môr a physgod); gwerth ac effeithiolrwydd y gwaith monitro hwn; dulliau o ddeall effeithiau posibl gwrthdrawiadau; y bylchau allweddol mewn data ac argymhellion ar gyfer ymchwil i'r dyfodol; ac, yn olaf, sut y gellid trosglwyddo'r holl wybodaeth hon, o bosib, i ddatblygiadau llif llanw yn nyfroedd Cymru.

Darganfu'r adolygiad hwn fod technegau monitro yn y maes a ddefnyddiwyd i benderfynu patrymau dosbarthiad gofodol-amserol anifeiliaid morol (yn bennaf mamaliaid morol ac adar môr) wedi darparu gwybodaeth werthfawr ar gyfer disgrifio presenoldeb, dosbarthiad a bregusrwydd tebygol rhywogaethau o ran dyfeisiau llif llanw. Cafodd yr astudiaethau arsylwi gweledol cychwynnol hyn eu cwblhau cyn i ddyfais gael ei gosod (monitro gwaelodlin) ac ar ôl ei gosod (monitro effaith) fel ei bod yn bosib monitro symudiadau mewn dosbarthiad (e.e. osgoi o bell). Maent hefyd yn darparu amcangyfrifon dwysedd sy'n baramedr mewnbwn angenrheidiol ar gyfer modelu risg gwrthdrawiadau. Nid yw'r dulliau hyn yn darparu tystiolaeth uniongyrchol o wrthdrawiadau ond maent yn galluogi'r gwaith o asesu a monitro rhai o'r effeithiau a achosir o ganlyniad i osod y dyfeisiau.

Hyd yn hyn, nid yw'r un o'r astudiaethau monitro ar famaliaid morol ac adar môr wedi cofnodi gwrthdrawiad uniongyrchol yn erbyn dyfais lanwol. Fodd bynnag, bu problemau methodolegol (e.e. cymal diffodd, diffyg dadansoddi'r holl ddata oedd ar gael a/neu ddiffyg monitro gwirioneddol o wrthdrawiad uniongyrchol) sy'n awgrymu na fyddai gwrthdrawiad wedi cael ei ganfod pe byddai wedi digwydd. Cofnodwyd gwrthdrawiadau yn erbyn tyrbinau llanwol mewn un o'r astudiaethau monitro ar bysgod, yn arbennig pysgod ifanc sy'n heigio. Ceir prinder o ddata monitro gan mai nifer fach yn unig o ddyfeisiau llanwol sydd wedi'u gosod a'u monitro hyd yn hyn. Er hyn, mae'r data sydd wedi'i gasglu hyd yn hyn yn darparu tystiolaeth werthfawr ar ymddygiad (e.e. osgoi o bell) a gorgyffyrddiad tebygol gwahanol rywogaethau morol o gwmpas dyfeisiau. Mae data symudiadau tri dimensiwn ar raddfa fân, trwy ddyfeisiau telemetreg a hydroacwstig, wedi darparu ychydig o dystiolaeth gychwynnol ar achosion o osgoi agos. Fodd bynnag, mae'r dulliau hyn yn gymharol gostus ac yn cynhyrchu maint sylweddol o ddata sydd angen llawer o amser ac adnoddau i'w brosesu a dadansoddi.

Modelu sy'n parhau i fod y dull mwyaf cyffredin a ddefnyddir er mwyn asesu risg gwrthdrawiad o ran anifeiliaid y môr. Mae amrediad o offerynnau modelu risg gwrthdrawiadau ar gael, a phob un ohonynt â gofynion paramedr mewnbwn a rhagdybiaethau gwahanol, sydd yn aml yn geidwadol. Mae'n ymddengys mai dilysiad cyfyngedig o'r modelau hyn a gafwyd o ran y canlyniadau monitro yn ystod y cyfnod gweithredol. Felly, lefel isel o hyder sydd yng nghanlyniadau'r offerynnau modelu hyn, ond, hyd yn hyn, dyma yw'r ffordd orau o asesu'r risg bosibl o ran gwrthdrawiadau.

Mae'r bylchau allweddol mewn tystiolaeth ar gyfer pob anifail morol yn ymwneud â chyfraddau osgoi neu daro, a hefyd cadarnhau os yw gwrthdrawiad gwirioneddol wedi digwydd a beth fyddai effeithiau gwrthdrawiad. Yn ogystal, mae'r data monitro cyfyngedig sydd ar gael ar hyn o bryd yn benodol i rywogaethau, lleoliadau a dyfeisiau, ac felly efallai na fydd modd ei drosglwyddo, neu na fydd modd ei gymhwyso, i waith asesu prosiectau llif llanw eraill. Mae bylchau allweddol eraill yn cynnwys goblygiadau posibl marwolaeth o ganlyniad i wrthdrawiad ar lefel y boblogaeth a'r effeithiau cronnus yn sgil gosod dyfeisiau ac araeau llanwol lluosog yn yr amgylchedd morol.

Un o'r prif argymhellion ar gyfer ymdrin â'r bylchau allweddol hyn yw casglu tystiolaeth bellach ar ymddygiad o dan y dŵr (gan gynnwys osgoi agos) fel ei bod yn bosib creu cyfraddau osgoi cadarn. Gellid archwilio technolegau eraill, fel synwyryddion gwasgedd a osodir ar lafnau neu ddelweddau hydroacwstig (sy'n dechnoleg sy'n datblygu'n gyflym), a'u datblygu ymhellach er mwyn cadarnhau a ydynt yn effeithiol wrth benderfynu a oes gwrthdrawiad wedi digwydd. Mae'n ofynnol hefyd casglu rhagor o wybodaeth o ran goblygiadau ffisegol gwrthdrawiad (â'r llafn neu'r differyn yn y gwasgedd) er mwyn deall y posibilrwydd o farwolaeth neu anaf yn llawn.

Efallai y bydd rhywfaint o dystiolaeth berthnasol neu wersi y gellir eu dysgu o fathau tebyg eraill o ddatblygiad (e.e. lagwnau llanwol neu brosiectau amrediad llanw) sydd â'r potensial i arwain at wrthdrawiad, ond canolbwyntiodd yr adolygiad hwn yn gyfan gwbl ar ddyfeisiau llanw llif. O ddiddordeb arbennig yw effaith unrhyw ddifferyn mewn gwasgedd a achoswyd gan y llafnau wrth iddynt droi. Cynhaliwyd ymchwil i hyn mewn dyfeisiau ynni cefnforol eraill ond prin yw'r dystiolaeth sydd ar gael o ddyfeisiau llif llanw ar hyn o bryd.

2. Executive summary

The potential for collision between marine animals and tidal stream devices is a concern in relation to consenting such deployments due to current uncertainties. NRW commissioned ABPmer to collate and review any available data collected from in situ devices and the wider literature that investigated collision between marine mammals, seabirds and fish and tidal stream devices. Based on the outcomes of this review, recommendations are provided on the key outstanding evidence gaps that need to be resolved to further support consenting and assessment of developments within this sector in Wales.

The approach to this evidence review comprised three key tasks. Task 1 involved identifying all planned and implemented tidal stream projects globally and determining their assessment and monitoring of potential collision. From this, a subset of 21 tidal stream devices/developers/projects that had monitored or assessed the risk of collision was selected to inform this evidence review.

Task 2 involved setting up a standardised template to collate details of the collision monitoring and assessment for each of the selected tidal stream projects. This was designed to ensure the evidence was captured in a consistent manner, with all results provided in a separate spreadsheet. An additional spreadsheet was also provided containing a wide range of literature relating to potential collision between marine animals and tidal stream devices; monitoring methods; environmental statements; collision risk modelling and any other relevant literature

Task 3 involved gathering monitoring data and information from the selected tidal stream developments/devices from a number of sources, including discussions with tidal stream developers and academics as well as reviewing environmental assessments, monitoring reports and wider literature from peer-reviewed research and strategic reviews. A review of this information was then undertaken to determine: the current methods of monitoring potential collisions between tidal stream devices and each of the three marine animal receptor groups (marine mammals, seabirds and fish); the value and effectiveness of this monitoring; approaches to understanding potential impacts of collision; the key data gaps and recommendations for future research; and finally, how all this knowledge could potentially be transferred to tidal stream developments within Welsh Waters.

This review found that field monitoring techniques used to determine the spatial-temporal distribution patterns of marine animals (mainly marine mammals and seabirds), provided valuable information for describing the presence, distribution and likely vulnerability of species to tidal stream devices. These initial visual observation studies were undertaken both before the installation of a device (baseline monitoring) and after its deployment (impact monitoring) enabling distribution shifts (e.g. far field avoidance) to be monitored. They also provide density estimates that are a necessary input parameter for collision risk modelling. These methods do not provide direct evidence of collision but enable some of the consequences of installation of the devices to be assessed and monitored.

To date, none of the monitoring studies on marine mammals and seabirds have been able to record a direct collision with a tidal device. This may reflect an absence of collisions or because of methodological limitations (e.g. shut down clause, no analysis of all available data and/or no actual monitoring of direct collision) that may have prevented detection of a collision even if it had occurred. One of the monitoring studies undertaken on fish have recorded collisions with tidal turbines, particularly shoaling juvenile fish. There is a paucity of monitoring data because there have only been a small number of tidal devices deployed and monitored thus far. Despite this, the data that has been collected to date provides valuable evidence on the behaviour (e.g. far-field avoidance) and likely overlap of different marine species around devices. Fine-scale 3D movement data, through telemetry and hydroacoustic devices, has provided some initial evidence for near-field evasions. However, these methods are relatively costly and generate a considerable amount of data which require a large amount of time and resource to process and analyse.

Modelling continues to be the most commonly used approach to assess the risk of collision of marine animals. There are a range of collision risk modelling tools available, each with different input parameter requirements and assumptions which are often conservative. There appears to have been limited validation of these models with the results of monitoring during operation. The level of confidence in the outputs of these modelling tools is therefore low, but to date, they are still the best way to assess the potential risk of collision.

The key evidence gaps for all marine animals relate to avoidance or encounter rates, as well as confirming if an actual collision has occurred and what the effects of a collision would be. In addition, the limited monitoring data that is currently available is species, location and device specific and may therefore, not be transferable or applicable to the assessment of other tidal stream projects. Other key gaps are the potential implication of collision mortality at the population level and the cumulative effects of deploying multiple tidal devices and arrays in the marine environment.

One of the main recommendations for addressing these key gaps is to collect further evidence on underwater behaviour (including near field evasion) to be able to generate robust avoidance rates. Other technologies, such as blade mounted pressure sensors or rapidly improving hydroacoustic imagery, could be explored and developed further in order to confirm if they are effective in determining a collision event. More information on the physical consequences of a collision (with the blade or pressure differential) is also required to fully understand the potential for death or injury.

There may be some relevant evidence or lessons that can be learned from other similar types of development (e.g. tidal lagoons or tidal range projects) that have the potential to result in a collision, but this review focussed wholly on tidal stream devices. Of particular interest is the impact and effect of any pressure differential, caused by the rotating blades, this has been studied in other ocean energy devices but available evidence from tidal stream devices is currently lacking.

3. Introduction

The marine renewable energy industry is expanding globally in response to concern around the impacts of climate change and increased energy demands. Within the UK, Wales has the potential for the development of diverse marine renewable technologies (Roche et al., 2016). In line with Welsh Government's road to decarbonisation there are aspirations to increase the contribution of marine renewable energy to Wales' electricity generation, and the recent introduction of demonstration zones for tidal energy aims to facilitate developers in device deployment (Roche et al., 2016; Welsh Government, 2019).

Potential collisions with marine animals are a concern in relation to consenting tidal stream energy deployments and a high level of uncertainty surrounds the likelihood of collisions and the population consequences (e.g. mortality). NRW commissioned ABPmer to review available evidence about the interaction and collision risk of seabirds, fish and mammals with tidal stream energy devices.

This study has involved collating and evaluating existing evidence from tidal stream deployments in the UK and worldwide. Recommendations are provided on how the findings of the study can be used by NRW to advise on the development of the evidence to support the growth of tidal stream energy sector in Wales while ensuring the sustainable management of natural resources.

The key objectives of this study were to:

- Determine the overall status of evidence relating to collision;
- Evaluate the value and effectiveness of monitoring and other approaches to understanding potential collision risk;
- Undertake a gap analysis to understand the further data and information requirements and associated recommendations for future research; and
- Consider how the evidence can be applied to potential tidal stream energy developments in Wales in the knowledge of the levels of confidence and outstanding uncertainties.

In this study 'collision' refers to the situation in which a transit through the swept area of a tidal turbine would be predicted to result in either a direct physical contact between the individual animal and the turbine blade or an indirect impact as a result of the pressure differential associated with the turbine blade. These interactions have the potential to result in injury or death. Where the text refers to 'collision risk', this is the probability of collision for an animal when making a single transit through the swept area of a turbine. Once account is taken of the likely number of such transits, 'collision rate' is the overall number of collisions estimated within a given period (usually one year). These estimates can then be used to determine the potential consequences for the population.

The main approaches that are used to assess the potential risk of collision between tidal energy devices and marine animals are modelling tools, monitoring in the field and laboratory studies. These different approaches are described in general terms below. Further detail is provided in the subsequent evidence review with illustrated examples.

Models allow for an estimate of the number of individuals of different species that might collide with a turbine device to be predicted. Simple models assume equal distribution of animals through the water column and at different times of tide, day and season. More complex models incorporate depth distribution information and may be refined for particular species or for a specific device design. The three main types of model available to determine the potential collision rate in marine mammals and seabirds (and which could also be used modified for fish) are the Encounter Rate Model (ERM), the Collision Risk Model (CRM) and the Exposure Time Population Model (ETPM). Existing fish collision risk models include kinematic models and agent-based models. Available models tend to assume there is no avoidance action taken by animals. Avoidance rate is considered separately as part of the assessment process and is usually based on judgement. Models also tend to assume that all collisions are fatal, irrespective of the blade speed, which varies with tidal speed, blade length and distance along blade (increasing blade speed with distance from hub).

There are three main basic approaches to collision monitoring in the field. One involves recording the spatial-temporal distribution of animals to estimate their density and determine the probability of encounters with a device. The second is directly recording the near or “far field” behaviour (e.g. avoidance or evasion, respectively) and collision of animals with operating turbines. The third is the opportunity to examine the physical consequences of potential collisions through post mortem examination and/or necropsy of stranding individuals. Laboratory studies have also been used to assess the collision risk of various turbine blade designs and survival rates of animals following a strike.

The information collated during field monitoring can be used to provide the required input parameter data into models (e.g. density estimates) and/or to refine model predictions of collision risk and collision/avoidance rate. Each of the monitoring approaches has different strengths and limitations which can affect the level, resolution and/or quality of the data that can be collected. This limits the extent of model validation, which in turn affects the confidence in the modelled outputs, as well as what the results might mean for predictions of population level effects.

Estimation of population level effects can be undertaken using population models which take account of population dynamics (fecundity, lifespan etc). Such population models have been applied to seabirds in relation to onshore and offshore wind farm collision mortality, fish in relation to commercial fishing and power station cooling water entrapment and for marine mammals in relation to by-catch and tidal turbine collision mortality.

A more detailed review of the main approaches outlined above available to determine collision risk of different marine animals (namely marine mammals, seabirds and fish) with tidal turbine devices has been undertaken and is provided in the following section. This review examined the available evidence that has been gathered by several planned and implemented tidal stream projects in the UK, Europe and North America.

The report has been structured as follows:

- Introduction – provides background context as to what is included within the study and sets out the key objectives to the study;
- Approach – presents an outline of the method applied to inform the project objectives;
- Evidence review – presents the main findings of the review structured according to key receptor groups (marine mammals, seabirds and fish); and

- Discussion – provides a summary of the key project findings, data gaps and recommendations.

4. Approach

The Evidence Review captured information from tidal stream projects that are planned and/or have been implemented as well as wider literature sources. This included discussions with tidal stream developers and academics whose research is focussed on collision risk as well as the review of environmental assessments, monitoring reports and wider published materials.

The method followed for this Evidence Review was split into three key inter-linked tasks as outlined below:

- Task 1 – Identify past, present and future tidal stream deployments for which evidence on collision might be available;
- Task 2 – Create a standardised template to capture details of the collision evidence for each of the planned/implemented tidal stream projects; and
- Task 3 – Evidence gathering and reporting.

Each of these tasks is explained in greater detail below.

4.1. Task 1 – Identified series of projects/devices

The most comprehensive list of planned and implemented tidal stream projects, both in the UK and overseas, is hosted on the Tethys website (tethys.pnnl.gov). This combined with both NRW and ABPmer knowledge was used to develop an over-arching list of tidal stream projects (see Appendix A). Key characteristics of each of the identified projects were collated to determine their potential relevance to understanding collision risk. This included consideration of the following, and allowed prioritisation of efforts as part of the evidence review process:

- Developer;
- Device
- Project;
- Location;
- Status; and
- Monitoring & Reporting.

From this list of tidal stream projects, a subset were selected to inform the evidence review process. This resulted in a total of 21 projects being captured within the evidence review including planned deployments, for which the likelihood of collision has been evaluated at a pre-consented stage:

- Minesto – Deep Green Tidal Kite
- Tidal Energy Ltd – DeltaStream turbine
- Mentor Mon (Morlais Energy)
- EMEC – Multiple: Demonstration area
- Nova Innovation – NOVA M100 Turbine
- SIMEC Atlantis Energy – MeyGen and SeaGen
- SmartBay – Multiple: Demonstration area
- Atlantis Marine Energy Test Site– Multiple: Demonstration area
- Atlantis Operations – Atlantis Resources AR1500 turbine

- Cape Sharp Tidal – OpenHydro turbine
- FORCE – Multiple: Demonstration area
- Sustainable Marine Energy: PLAT-1 and PLAT-0
- Clean Current – Clean Current Turbine
- Ocean Renewable Power – RivGen and TideGen
- Verdant Power – Gen4 Free Flow
- Atlantis Resources – AK-1000
- Perpetuus – Multiple: Demonstration area
- Sabella – D10 turbine
- SEENEOH – Multiple: Riverine test area

The list of devices/deployments to be considered within the evidence review was agreed with NRW at the project inception phase. Several projects were not progressed within the review either due to a lack of data availability or lack of progress with the development (see Appendix A for full list of devices, information on location, technologies, and reasons behind screening out/in).

4.2. Task 2 – Set up a standardised evidence template

A standardised template was set up to capture details of the collision risk evidence base for each of the planned/implemented tidal stream projects. This was designed to ensure the evidence was captured in a consistent manner for each of the projects reviewed.

An excel spreadsheet was set up in which to capture the evidence. The first tab of the evidence spreadsheet presents key information for each of the reviewed projects (see Table 1). The subsequent tabs within the spreadsheet contain more detailed information for each of the identified projects (Table 2). A separate references spreadsheet has also been produced to provide a comprehensive source of current tidal stream collision risk literature (Table 3).

Table 1: Overview of devices and developers: Evidence spreadsheet.

Parameter	Description
Developer	Name of developer
Device	Details of the type of device that has been/will be deployed
Project	Project name
Location	Project location
Years Deployed/ Operational	Timescales of device deployment
Development stage	Project status, either - Pre-consent/in development, Consented, Deployed or Decommissioned
Assessment of Environmental Effects	A signpost as to how the potential collision risk has been evaluated for each receptor type. This is further broken down in to: • Theoretical – Modelling • Monitoring Pre-construction • Monitoring Post-construction
Data availability	An indication as to whether the respective data is publicly available (and where it is held)
Key references	Key references of relevance to that project

Table 2: Parameters assessed for each tidal development: Evidence spreadsheet.

Parameter	Description
Developer	Name of developer
Device	Details of the type of device that has been/will be deployed
Project	Project name
Location	Project location
Years Deployed	Timescales of device deployment
Current Status	Project status, either - Pre-consent/in development, Consented, Deployed, Decommissioned or Not operational
Assessment and Monitoring Undertaken	Summary of the project specific evidence collected for the development through: • Modelling • Monitoring Pre-construction • Monitoring Post-construction This has been further broken down for each receptor type
Results from monitoring	Results of any *in situ* monitoring undertaken for both pre-construction (baseline) and post-construction (operational) monitoring. This has been broken down for each receptor type
Limitations of monitoring	Constraints associated with pre- and post-construction monitoring results
Limitations of modelling	Constraints associated with modelling results
References	Key reference of relevance to a particular project

Table 3: References spreadsheet.

Parameter	Description
Reference Number	Internal reference provided to each report. This links to the reference numbers provided in the evidence spreadsheet
Year	Year report was published
First author	First Author or Company Name
Additional authors	Other named authors or contributors
Title	Report title
Journal/ Report Number	The publishing journal for the report and report number or reference
Type	The form of the report. This was categorised as: • Research Paper (Original research) • Research Paper (Review article) • Book chapter • Conference Presentation • Scoping Report (EIA) • Environmental Statement (EIA) • Environmental Appraisal • HRA • SEA • Technical Report • Website page
Link	Website link to the report for online access where available

4.3 Task 3 – Evidence gathering and gap analysis

Evidence gathering was focused solely on projects related to tidal stream energy developments. It is acknowledged that wider evidence (including assessment of number of collision events through modelling) and monitoring techniques are available for other forms of green energy devices however these fell outside the scope of this review. Collision risk evidence was gathered from a number of sources including:

- Project specific details in the form of environmental assessments, application and post consent monitoring documentation;
- Interviews with developers and academics working in the field of tidal stream collision risk; and
- Literature review.

Evidence was sourced from tidal stream developments in the UK and worldwide. This was designed to capture all available data and evidence to inform collision risk assessment and to identify any knowledge which could potentially be transferred to tidal stream developments within Welsh Waters.

The types of project specific documentation reviewed included Environmental Statements, Habitats Regulations Assessments, as well as wider assessment and application details. These were extracted from publicly available sources such as the Tethys website, The Crown Estate's Marine Data Exchange, the Marine Management Organisation's (MMO) marine licence public register (Marine Case Management System (MCMS)), local authorities' planning portals, planning inspectorate's website and/or individual developers' websites.

Contact was made with over 36 individuals at 30 organisations (including developers, academics and industry bodies) to try to obtain evidence in relation to collisions which is not necessarily in the public domain. A full list of organisations contacted can be found in Appendix B. A total of 18 responses were received in answer to this information request.

Interviews were held with five developers/demonstration areas to obtain further evidence, or clarification, with respect to their individual projects and any wider experiences with respect to collision risk (European Marine Energy Centre (EMEC) (Scotland), Morlais (Wales), NOVA Innovation (Scotland), SEENEOH (France) and Sustainable Marine Energy (Canada)). The main point of the telephone interviews was to understand the amount and type of monitoring that had been undertaken for the tidal device or at the test centre. Additionally, the success and limitations of the different monitoring techniques undertaken were discussed to understand which types of monitoring were not practical or feasible. It was also requested that where available, any unpublished monitoring data were shared with the project team to further develop the evidence base. Where information has been provided from these telephone interviews it is referenced within the separate Evidence Spreadsheet.

Similarly, discussions were also held with academics from two universities (Swansea, and Bangor) to understand the nature of ongoing research studies and how these contribute to the tidal stream collision risk evidence base.

A wider literature review was undertaken to determine the current state of knowledge on collision risk with tidal stream devices globally. This included both published research papers as well as strategic reviews (e.g. Ocean Energy Systems Technology Collaboration Programme (OES) and The Offshore Renewables Joint Industry Programme ORJIP).

Search tools such as ScienceDirect and Google Scholar were used to identify key literature. A systematic approach was used to identify literature through the use of pre-defined search terms.

The tidal stream collision risk evidence derived from each of these sources was synthesised for each of the main receptor types (marine mammals, seabirds and fish). The evidence is detailed within the supporting standardised evidence templates and summarised in the subsequent sections of this report. An assessment of the effectiveness and limitations of the evidence for each receptor has also been discussed below. Additionally, in all instances, where it was not possible to get hold of the actual data or evidence this has been signposted within the evidence spreadsheet.

Once the evidence had been collated gaps within the current knowledge were identified.

5. Evidence review

A synthesis of the results from the evidence review and an assessment of the predicted collision between marine mammals, seabirds and fish and tidal stream devices is provided below and within the separate evidence spreadsheet. Each section aims to review:

- The overall status of the evidence relating to collision by summarising in situ monitoring approaches that have been used to date and looking at wider evidence (including modelling techniques that have been employed to predict number of collisions, wider academic literature and non field-based studies);
- The potential value and/or limitation of monitoring approaches to understanding potential collision between tidal stream energy devices and marine animals; and
- Any gaps in data/information requirements to collision assessment.

Consideration has been given to how the evidence can be applied to potential tidal stream energy developments in Wales throughout the review accounting for the levels of confidence and outstanding uncertainties with the current monitoring approaches

5.1. Marine mammals

Marine mammals are regularly recorded foraging within high energy environments indicating a potential risk of collision with tidal stream devices (Benjamins et al., 2015; Copping et al., 2016). This spatial overlap means that the potential risk of collision with such devices requires full consideration when evaluating the impacts that could arise from a project. Marine mammals are offered high levels of international protection with any detrimental effect needed to be fully assessed and mitigated where necessary. Several species of marine mammal have small population sizes and therefore even a small number of injuries/mortalities could have potential population level impacts and therefore risk of collision is an especially challenging consenting risk for the industry.

5.1.1. Monitoring approaches

Monitoring to understand the potential for collision between marine mammals and tidal stream devices, and the effect of these collisions, has been undertaken through three main approaches:

- The first approach focuses on observing the spatial-temporal overlap between marine mammals and the tidal stream device, and therefore the probability of encounters. This approach also monitors far field avoidance;
- The second approach focuses directly on detecting collision and monitoring near field evasion with tidal stream devices; and
- The third approach looks at the aftermath of a potential collision through post mortem examination and/or necropsy.

Spatial and temporal overlap

The first monitoring approach aims to map the distribution and density of species within the vicinity of a proposed and/or operational tidal stream deployment. This can be achieved by using visual observations via vantage point, boat or aerial surveys (for cetaceans and seals), by placing data loggers onto the animals (for seals only) or by acoustic surveys (cetaceans only). Each of these survey types have different methodologies depending on the geography of the tidal stream area.

Vantage point, boat and aerial surveys are the most common example of monitoring that is undertaken to provide baseline information in the vicinity of a proposed device and is often continued post-deployment to understand the behavioural response of marine mammals. The vast majority of projects included within this Evidence Review have undertaken some form of visual observation. Vantage point surveys are undertaken from a set location, scanning the near-field environment at regular intervals. The scanned area is usually divided into sections to help with spatial analysis. These surveys are limited to daylight hours and the difficulty of accurately locating sightings over large distances is well known (JNCC, 2005). Boat and aerial surveys are undertaken along pre-defined transects often zig-zagging over the device footprint with one or two trained observers recording all species of marine mammal observed and the location of each sighting. Aerial surveys, including digital aerial surveys, can be undertaken over a large area but analysis to species level can sometimes be difficult (Hammond et al., 2017).

Data loggers can be glued onto the heads/back of seals to provide data on fine-scale movement patterns (Hastie et al.¸ 2014). Within each datalogger a wide variety of sensors can be housed including time-depth recorders, satellite positioning (e.g. global positioning system (GPS)), accelerometers, and magnetometers. Each sensor provides a different parameter which potentially can then be interpreted together to produce fine-scale 3D movements and evidence of behaviour (e.g. rapid swim away from a turbine). However, they are attached to only a small sample of the population. These loggers can be limited by battery life, storage availability and can only transmit data on surfacing and connecting with satellites or when animals are recaptured. The more sensors within the device the greater the battery drain, and more data storage capacity needed. Another limitation of applying data loggers is that there is also potential that once deployed the seal may not return to the same haul out site again, this can be overcome by using certain technologies that transmit data remotely.

Cetaceans are vocal organisms and the vocalisations can be recorded using acoustic devices to understand distribution, behaviour, relative abundance and other aspects of ecology (Zimmer, 2011). Acoustic receivers (such as hydrophones, C-PODS, T-PODS, or SoundTraps) may be placed close to the tidal stream device, in the surrounding area, or on the devices themselves. These passive acoustic monitoring (PAM) devices are placed at either the surface or seabed and detect acoustic signals at a set frequency. Single acoustic receivers can show the presence/absence of marine mammals, but multiple devices can be placed within an array or cluster to locate and detect movement of animals by investigating the detection rate/intensity at the varying devices (Hastie et al., 2014; Williamson et al., 2015; Malinka et al., 2018). PAM can be undertaken 24 hours a day in turbid environments, making it appropriate for these high energy environments with several multi-year studies undertaken to date (Zimmer, 2011; Tollit et al., 2019). There are, however, some limitations; for example, cetaceans are not constantly vocalising so there is the potential not to detect some individuals. The range of PAM is limited, and cetacean sound is also directional, meaning animals swimming away from the device may not be detected.

Direct collision monitoring

Direct monitoring approaches to detect collision use either technologies which can “see” the device, through hydroacoustic monitoring (e.g. sonar or echosounders) or underwater video cameras or technologies which monitor impacts with tidal stream devices (e.g. accelerometers or strain gauges) but does not distinguish between objects (debris or animals).

Modern hydroacoustic imaging devices (e.g. sonar, echosounders, split- and multi-beam devices), operating at high frequencies, can acquire detailed acoustic images of the underwater environment. Variables such as occurrence, size class and behaviour of a variety of aquatic species of fish, seabirds, and mammals that occur in high energy marine environments can be monitored using imaging sonar systems. The specific approach to the deployment of such acoustic devices has varied between studies and sites. To date hydroacoustic devices have been incorporated into the tidal stream device or positioned on specifically designed platforms set away from the tidal stream device (Hastie et al., 2014; Williamson et al., 2015). Each device differs in the technology used, but in general hydroacoustic devices pulse acoustic energy from the echosounder via a transducer which is reflected off the animal/object. The high pulse frequency enables movement to be detected and tracked through the observational window.

In order to ascertain the movement patterns of each marine mammal species, computer algorithms have been developed to automatically assign a detection to a certain species. This has been achieved by hydroacoustic devices that were mounted on a vessel to provide worked examples of each species’ movement pattern (Hastie, 2013; Hastie et al., 2019). This automation of detections is critical in the future deployment of hydroacoustic devices in order to increase processing speed by reducing human involvement which currently is a major limitation for this type of monitoring.

The placement, observational window and frequency of recording varies between studies but will result in a trade-off between data resolution and field of data capture. Only echosounder instruments 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. The functionality of echosounders in energetic environments has so far been limited due to the operational difficulties of data collection in such conditions and the intense interference caused by backscatter related to turbulence (Fraser et al., 2017; Fox et al., 2018). Another limitation of hydroacoustic monitoring is the large amount of data produced, which is then time consuming to analyse and restricts the ability to have long-term datasets (Hastie et al., 2019).

Underwater video techniques involve the placement of a camera system on the turbine structure to record the presence of marine mammals in the vicinity of the turbine. Where possible the passage of species through the turbine device to capture any collision and/or injury is overserved/recoded. One key limitation of video systems is that due to light requirements they are only able to capture data during daylight hours, at certain depths and turbidity levels. 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. Cameras are also prone to biofouling. Footage collected can provide clear evidence of collision or injury caused to marine mammals, however data analysis is extremely time consuming.

Accelerometers and strain gauges have been placed on tidal stream devices with the primary purpose of monitoring the physiological stress on the blades as the device is operational. These monitoring devices could also provide an indication, through adverse parameters, as to when an object collides with the blade. Marine mammals have the largest mass and it is likely that if an animal was to collide with the blade any vibration or reduction in velocity of the blade should be recorded. The main limitation is that the amount of deviation from a normal reading that would indicate a collision is unknown. Even if an abnormal reading is recorded (indicating a collision) there is no way of knowing what object it was.

Individual consequences of collision

The third approach to monitoring collisions in marine mammals is to understand the consequences of collision to the individual. This can involve searching and then investigating stranded (either alive or dead) marine mammals and looking for any signs of impact. If a collision occurs, it is unknown whether a lethal or sublethal injury could occur. Investigation of any carcasses within the vicinity of a tidal device and wider region could provide further information on the potential impact injury. However, after finding an injured carcass it would be hard to ascertain how and when this injury occurred, so there are major caveats to this monitoring. If there was an overall increase in strandings with similar injuries within the vicinity of a new device/operation then this method could allude to a direct impact; however, there would be high levels of uncertainty of causation.

The potential impact of a blade can also be assessed theoretically based on a series of physiological and biological assumptions. This type of prediction has been supported by studies using dead carcasses and subjecting them to strikes in water from an object similar to a blade or investigating tissue tensile strength (Carlson et al., 2014; Copping et al., 2017; Onoufriou et al., 2019).

5.1.2. Monitoring studies and results

Since the first deployment of a tidal turbine several developers have undertaken in situ monitoring to record marine mammal species in the vicinity of tidal devices. Multiple approaches, as discussed above, have been used for monitoring potential collision risk, with varying degrees of success. This section reviews some of the monitoring undertaken across a range of developments, summarises the findings of the monitoring with regards to collision risk and discusses any limitations of the findings.

Marine Current Turbines'(MCT) SeaGen device (now owned by SIMEC Atlantis) provides the best example of a long-term project that has undertaken multiple examples of monitoring (both pre-deployment and during operation). The project was located in Strangford Lough, Northern Ireland and involved implementing a range of monitoring approaches between 2005 (pre-deployment) until decommissioning and removal in 2018/19.

Over the lifetime of the project several of the monitoring approaches (described above) have been undertaken within the vicinity of the device. These comprised visual observations via boat, aerial, shore and device-based surveys, harbour seal telemetry, passive acoustic monitoring (via Timed POrpoise Detectors (T-PODs)), carcass post mortems and active SONAR (Royal Haskoning, 2011; Hastie et al.¸ 2014; Savidge et al., 2014).

Following the initial commissioning of the device, three years of monitoring was required in accordance with the Environment Monitoring Plan (2008 to 2011). This monitoring concluded that there were “no major impacts on marine mammals” (Royal Haskoning, 2011). The monitoring identified a slight change in the distribution of species, but no barrier effect or reduction in the overall population size (through seal haul-out sites aerial monitoring). It should be noted, however, that there was a licence condition to stop the operation of the device if a marine mammal was spotted within its vicinity. This meant near-scale evasion was not able to be ascertained from the monitoring, and direct collisions would be prevented. Initially the shutdown clause was for a 250 m buffer zone, but when the active sonar device was active, the shutdown clause was reduced to a 30 m buffer zone (Hastie et al., 2014; Savidge et al., 2014).

As direct collision monitoring was not able to be undertaken within Strangford Lough, novel techniques were used to see if a population level change could be detected. Biannual aerial surveys (from a helicopter and thermal imagery) of the known haul out sites within the Lough and wider region were undertaken between 2006 and 2014. There was a decline in number of seals at monitored haul out sites, but the rate of decline was continual since 2002, and not expected to have been impacted by the SeaGen device (Savidge et al., 2014).

More recent analysis of the harbour seal telemetry data collected between 2006 and 2010 looked in greater detail at any barrier effect and the number of transitions through the Narrows (via the device) (Joy et al., 2018; Sparling et al., 2018). Comparisons were made between data collected in 2006 (pre-deployment), 2008 (installation period) and 2010 (operational). The main conclusion drawn from this analysis was that the 32 tagged seals exhibited avoidance behaviour away from the operational device suggesting there was a reduction in potential collision risk. Sparling et al. (2018) demonstrated that the operational device reduced the number of transitions through the Narrows, by 20 % (overall) and 57 % (during daylight hours), however when transitions did occur, they were approximately 250 m either side of the device.

Using the same seal telemetry data, Joy et al. (2018) looked at how this monitoring could feed into collision risk models. By modelling the depth at which the seals transited past the device, the number of seals that pass through the “impact zone” was reduced by 90 % compared to modelling using only the 2D locational data. Within the study, only 10 % of the transit lines occurred at depths at which the device was located. Therefore, in addition to any avoidance/evasion, the period for which a seal is within the “impact zone” is greatly reduced.

Similar to MCT’s SeaGen device, Minesto’s quarter scale device was trialled in Strangford Lough between February 2013 and June 2014. The marine mammal observer present recorded a 95% reduction in the presence of seals within 50 m of the device following its deployment (Minesto, 2016). This supports the previous study that found the number of animals in the vicinity reduced during the operational phase.

Both devices and the respective monitoring within Strangford Lough were unable to monitor direct collision due to the shutdown licence condition described above. This means while there was empirical evidence relating to potential collision via near field evasion and far field avoidance, which can inform avoidance rates in CRM/ERM, there was no direct understanding of collision from either SeaGen or Minesto.

Different devices deployed within other locations have also monitored the spatial-temporal overlap between the device and marine mammals. EMEC’s wildlife observations data indicates there was a noticeable change in the distribution of marine mammals around the test devices (Long, 2017). Low densities of cetaceans made it difficult to draw conclusions on how they might have been affected. For seals, however, there was an initial decrease in abundance around the turbines on and immediately after installation. Numbers appeared to recover gradually thereafter, including when turbines were operational, although not to baseline levels. It is thought the initial decrease related to the associated increase in shipping activity rather than the presence or operation of the turbines.

Another method of monitoring spatial temporal overlap is PAM. PAM was undertaken around the DeltaStream device in Wales and at the Fundy Ocean Research Centre for Energy (FORCE) in Canada. Both the resulting analysis of the data indicated that harbour porpoise click detection reduced close to the device when the devices were operational (Joy et al., 2018; Malinka et al.¸ 2018; Tollit et al., 2019). Each study found that overall detection did not change but the number of detections decreased at the PAM devices closest to the device potentially suggesting avoidance behaviour was taken by harbour porpoise. Results found at the DeltaStream site indicate a preference for foraging at night with 71 % of harbour porpoise detections occurring during darkness. This limits the effectiveness of monitoring approaches involving visual observations which are commonly employed (Malinka et al., 2018). PAM at DeltraStream included arrays of hydrophones which allowed animals to be localised, resulted in three detections of porpoise close to the device when it was operational (Malinka et al., 2018).

The monitoring techniques used at MCT’s SeaGen to monitor direct collision (hydroacoustic monitoring) have also been replicated at other locations including EMEC and Ramsey Sound. However, the hydroacoustic device at EMEC (FLOWBEC) did not detect any marine mammals during six 14-day deployments and data at Ramsey Sound has not been publicly released (three months of deployment) (Williamson et al., 2017).

5.1.3. Wider evidence and assessment of collision

The wider evidence with respect to the risk of collision is also available through scientific literature as well as from modelling studies undertaken to inform impact assessments.

The most applicable models used in the assessment of collision between marine mammals and tidal devices are largely derived from offshore wind farm collision risk models (CRMs) (e.g. Band, 2000, Grant et al., 2014). Some of the models have been refined further for particular species (e.g. harbour seals, Band et al., 2016), or for a different device design (e.g. tidal kite, Schmitt et al., 2017). Often after a model has been run, the results are inserted into a Population Viability Analysis (PVA) to understand what the results mean for the affected population. Recent examples of CRM/ERM and then PVA analysis was undertaken for Morlais, due to unconfirmed phasing and number of devices, the range of outcomes were large, with several of the estimations (with no avoidance) indicating that the number of animals killed annually would be larger than the population size. This highlights the inaccuracy that can exist within some of these models, especially when no avoidance behaviour is factored in.

In summary there are three main types of model - ERMs, CRMs and Exposure Time Population Models (ETPM). Scottish Natural Heritage (SNH) undertook a detailed review of modelling methods for tidal stream devices. The review included a detailed outline of each model, the methods used to gather input parameters and guidance on how to undertake and interpret the results (SNH, 2016). The SNH review still provides the most in-depth overview of the knowledge on collision risk modelling and marine mammals. There has been more recent, device specific modelling which is described below.

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. 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. In both models, the shape of the rotor blades and animal are highly simplified, and single mean values are used for tidal current, animal and rotor speeds (Band et al., 2016; SNH, 2016).

The ETPM uses population modelling to assess the critical additional mortality due to collisions which would cause an adverse effect to 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.

Schmitt et al.’s (2017) model was refined for non-static devices within the water column and used real underwater movement data from Minesto’s tidal kite to define the parameters. The assumptions within the previously described models is that an animal swims at a constant speed perpendicular to the device and would therefore encounter the device at a certain rate. However, as the device moves in this case the rate of encounter would be lower.

All models have the limitation that they are only as good as the input data, and there is still an overall lack of understanding around near field evasion and far field avoidance of tidal stream devices by marine mammals, with an estimated avoidance rate between 0 and 100 % used in the SNH recommended CRM/ERM. In addition, the models presume that all collisions would result in mortality; this is unlikely for larger animals like marine mammals (Carlson et al., 2014; Copping et al., 2017). Work undertaken by Band et al. (2016) addressed some of the uncertainties by including refined input parameters by including telemetry derived movement data (Thompson et al., 2016) and reducing the likelihood of mortality if a collision event occurs.

The density of marine mammals used as an input parameter for the models suggested within SNH’s review are largely provided from visual observations, which as mentioned previously are susceptible to error. The density estimates will relate to number of mammals observed in two dimensions at the surface of the water, this does not account for use of the water column (i.e. three dimensions) described by dive time, dive depth or swimming profile, which will all impact on the potential collision risk. It is also possible that if turbines act as fish aggregation devices then this might alter mammal densities in the vicinity. Furthermore, current models are highly precautionary due to the large number of assumptions.

In addition to monitoring and modelling studies, wider investigations have also been undertaken to help understand collision risk, for example the impact of a collision for harbour and grey seals in Scotland, south resident killer whales in Canada and harbour seals in the USA has been examined (Onoufriou et al., 2019; Carlson et al., 2014; and Copping et al., 2017, respectively). Through direct field observations and lab studies Carson et al. (2014) and Copping et al. (2017) investigated dead stranded animals, taking tissue samples to understand the tensile strength of the samples and determining collision at varying points along the body at differing speeds. These studies concluded that collisions between the device and killer whales would likely lead to "some subcutaneous damage…while laceration of the skin is thought unlikely". This did not represent a lethal impact if a collision where to occur (Carlson et al., 2014). To understand the impacts on a smaller species, the same testing was done on harbour seals in the USA and the same conclusions were drawn. The chance of a serious, fatal injury occurring was estimated to be minimal (0.005 % chance). For this to a occur a unique set of circumstances had to happen whereby a marine mammal would need to hit the tip of the blade while the blade was at full rotational speed, with no avoidance behaviour shown. The likelihood of a sublethal effect occurring was concluded to be more likely (Copping et al., 2017).

Onoufriou et al. (2019) simulated the potential impacts of collision using dead seal carcasses (18 grey seals, and one harbour seal) and a boat, the keel of which had been modified at the bow to replicate a turbine blade. Pre- and post-impact x-rays were taken to assess the impact of the collision on the animal. The speed of the boat (blade), was the key factor in determining the level of injury and whether it could potentially be lethal, with speed greater than 5.1 m/s indicating lethal skeletal damage. During the study, 48 % of the collisions produced sufficient skeletal trauma to be considered likely to have been fatal. The study was heavily caveated, as there were multiple assumptions and acceptance of the oversimplified impact. There were also some caveats to the study, in terms of representing a worst-case example by using the thinnest part of the blade.

5.1.4. Summary of current knowledge

This section provides an overview of the empirical evidence from tidal stream devices and summarises the results for the monitoring approaches described above for marine mammals (see Table 4 for a summary of all monitoring techniques to date). Currently there is little actual monitoring data or limited direct evidence relating to collision risk between marine mammals and turbine devices and as such there is a large gap in current understanding of actual encounter rates as well as direct and indirect mortality rates in the event of a collision.

Several projects have recorded a distribution shift of marine mammals pre- and post-instalment, and then another shift, once operation has started. Avoidance behaviour has been exhibited at Strangford Lough, EMEC and DeltaStream. This reduces the spatial temporal overlap between marine mammals and tidal stream devices and therefore a reduction in potential collision that might have otherwise occurred. This far-field avoidance is understood to some extent, but each individual population of marine mammals is likely to exhibit a different response, and therefore the changes recorded elsewhere should not be presumed to apply to all populations. The spatial temporal patterns for some species derived from visual observations have shown a clear preference to certain tidal periods, applying a tidal restriction to operation could reduce potential risk.

Overall there is no evidence of an observed collision between a marine animal and a tidal stream device. However, this may be due to limitations of the monitoring methods (e.g. shut down clause, partial coverage of swept area, biofouling) indicating that if a collision had occurred it would have not been detected, and the small amount of operational time that has been monitored. The evidence gathered to date, indicated marine mammals show distribution shifts away from a device, suggesting some degree of far-field avoidance. However, there has not been enough information on near-field evasion to provide an overall conclusion about any near-field responses. The monitoring undertaken for these projects/studies has provided useful insights into animal movements within the vicinity of tidal turbines and have proven the potential applicability of several technologies.

If a collision were to occur, there is not enough information on what the impact on the individual would be. Current thinking suggests that all collisions may not be lethal, and would depend on how fast the rotors were turning and where on the bladed the collision occurred, with the sublethal effects hard to test and quantify (Copping et al., 2017; Onoufriou et al., 2019).

5.2. Seabirds

Seabirds are attracted to high tidal energy areas due to increased prey resources associated with the high-energy environment (Benjamins et al., 2015; Waggit et al., 2016). Most species of seabird are attracted to these high energy areas, but it is diving species that are likely to be affected the most, but all species might potentially be impacted by surface placed devices. Both surface diving species (e.g. auks and cormorants) and plunge diving species (e.g. gannets) can dive to depths at which a bottom mounted tidal device could be positioned (Furness et al., 2012). Surface foraging species (e.g. gulls and terns) could also be impacted from a surface device, with these species able to “dive” to one or two meters. This direct overlap between the swept area of the blade/device and a foraging seabird means that a seabird could be struck by a blade (Langton et al., 2011; Furness et al., 2012; McCluskie et al., 2012; Benjamins et al., 2015).

5.2.1. Monitoring approaches

Monitoring to understand the potential risk of collision between seabirds and tidal stream devices has been undertaken through two main approaches:

- The first approach focuses on understanding the spatial-temporal overlap between seabirds and the tidal stream device, and therefore the probability of encounters; and
- The second approach focuses directly on monitoring collision with tidal stream devices.

Spatial and temporal overlap

Seabirds are recorded during the same visual observation surveys as marine mammals, with experienced personal able to record both seabirds and marine mammals concurrently. Due to the size of some seabird species, there are increased challenges of correctly identifying and placing individual seabirds into the correct section to provide fine-scale distribution data (Waggit et al., 2014). The range of successful species identification is reduced compared to marine mammals. New technologies that incorporate laser range finders into binoculars have been used during visual surveys to increase the accuracy of the sighting locations (Cole et al.¸ 2019).

Like marine mammal monitoring, boat and aerial surveys are undertaken along pre-defined transects often zig-zagging over the device footprint with one or two trained observers recording all species of seabird observed and the location of each sighting. Aerial surveys, including digital aerial surveys, are used to survey large areas quickly and particular areas where certain species of seabird are known to be easily flushed (fly away or dive) e.g. divers and seaducks by the presence of a boat. If seabirds are flushed outwith the detection area (common for sensitive species) the estimate calculated after the survey may underestimate the true number of seabirds present. However, some species are harder to observe from the aerial surveys due to their size and colouration (e.g. species with dark feathering on the upperparts can be overlooked, due to the feathering blending into the sea when viewed dorsally).

Data loggers have been glued onto the back of seabirds or attached via a harness providing fine-scale movement patterns. Within each datalogger a wide variety of sensors can be housed including time-depth recorders, satellite positioning (e.g. global positioning system (GPS)) and accelerometers. Each sensor provides a different parameter which can then be interpreted together to produce fine-scale 3D movements and evidence of behaviour (Collins et al., 2015). These loggers can be limited by battery life, storage availability and accepted size of device in order to avoid impacting the seabird. The more sensors within the device, the greater the battery drain, and more data storage capacity needed and therefore the larger size. There is also potential that once deployed the seabird may not be recaptured. This is considered unlikely during the breeding season when seabirds need to return to the nest, but wintering patterns are very hard to ascertain. The most common deployment is for a short timeframe due to the size of the device (Owen, 2015; Shoji et al., 2015; Johnston et al., 2018).

Direct collision monitoring

Direct measures to determine collision use technologies which can “see” the device, either through hydroacoustic monitoring (e.g. sonar or echosounders) or underwater video cameras. In theory, these technologies could detect when an object, whether it be debris, or seabird directly collides with the device, but to date this has not happened. The methods that are used to detect seabirds are similar to the methods used to detect marine mammals, with all technologies applicable to both receptors. Please refer to Section 6.1.3 for full explanation of the monitoring approaches used.

A seabird specific limitation of the device, especially hydroacoustic, is that due to the small size of seabirds it is impossible to identify the species of seabird recorded (Williamson et al., 2017). Currently, to understand species specific direct collision monitoring, the use of video cameras is required. However, for future projects hydroacoustic monitoring could be used concurrently with either data loggers or vantage point surveys to identify which species are detected on the hydroacoustic monitoring device. In reality this would be time consuming and during mixed-species feeding would be virtually impossible.

5.2.2. Monitoring studies and results

Since the first in situ placing of a tidal turbine several developers have implemented monitoring to record seabird species in the vicinity of tidal stream devices. Multiple approaches, as discussed above, have been used for monitoring potential collision risk, with varying degrees of success. This section reviews some of the monitoring undertaken across a range of developments, summarises the findings of the monitoring with regard to collision between seabirds and tidal stream devices and discusses key limitations of the findings.

EMEC provides the best example in Europe of a long-term tidal stream energy project that has undertaken monitoring of seabirds (between 2005 and 2015) and published interpreted results (both pre-deployment and during operation). FORCE in Canada has also undertaken multiple years (2009 to 2012 for the baseline and then 2016 to present for operational) of monitoring and analysis of seabird distribution. Monitoring via visual observation through dedicated vantage point surveys and the use of hydroacoustic devices have been deployed in both locations to monitor seabird distribution and potential collision. Other projects/devices which have published data on seabirds include, SeaGen in Northern Ireland, Verdant Power in USA and DeltaStream in Wales.

During vantage point surveys at EMEC, FORCE and SeaGen changes in the distribution of seabird species between pre-deployment, instalment and operational phases were observed (Robbins, 2012; Savidge et al., 2014; Long, 2017; Envirosphere, 2018). Several seabird species increased in abundance in the vicinity of the device, for example cormorants were more abundant after the device was installed (but not operational), likely due to the devices acting as fish aggregation devices (FAD) (Long, 2017). Once the devices become operational a distribution shift was observed and avoidance occurred for some species (including cormorants and divers) (Long, 2017; Envirosphere, 2018). In contrast, Verdant Power’s Roosevelt Island Tidal Energy (RITE) Project observed no measurable change in the number of diving species following the installation of the devices (Double-breasted Cormorant specifically). However, it should be noted that the location of RITE restricted the number of seabirds present due to the urbanised riverine location close to New York (Verdant Power, 2010).

Acoustic monitoring of seabirds has often been a secondary aim of the hydroacoustic devices deployed at tidal stream projects. This is due to the difficulty in identifying species owing to the relatively small size of seabirds compared to marine mammals. However, several hydroacoustic devices have successfully tracked seabirds by tracking dives on acoustic imagery (Savidge et al., 2014). The FLOWBEC platform deployed at EMEC was specifically designed to monitor seabirds, by using novel algorithms that aid detection of seabirds within high energy areas (Williamson et al., 2019). Six trials lasting 14 days each detected a single seabird at both the control location and the location with a turbine present. During the short trial period the technology was proven, and the algorithms refined to ensure the technology would be able to record a collision (if one were to happen). Similarly, at the DeltaStream device in Ramsey Sound, the hydroacoustic device detected seabirds on multiple occasions, with no collision observed.

5.2.3. Wider evidence and assessment of collision

The wider evidence with respect to the risk of collision is also available through scientific literature as well as from modelling studies undertaken to inform impact assessments.

Similar to marine mammals, SNH undertook a detailed review of different models that predict collision between seabirds and tidal stream devices (see Section 5.1.3). The SNH review still provides the most comprehensive knowledge on modelling for seabirds. Several recent examples of the models are described below.

Recent assessments in support of applications for tidal stream projects have used both the CRM and ERM models to predict collision for seabirds. As there is no consensus on which is the most appropriate for use underwater both of the methods are often used (nrp, 2014: Minesto, 2016; Morlais, 2019). Similar input parameters are required for all of the models including, body length, time at the swept area depth, swim speed and density, but none are able to provide an avoidance rate, so each model includes avoidance estimates between 50 and 99 %. This wide variety of avoidance estimates means that worse case scenarios are often high (over 1 % of a population could be “struck” annually).

Studies evaluating potential for interaction have also considered seabird behaviour and environmental factors within highly energetic tidal areas. Some species of seabird are often recorded in largest numbers during periods of lowest tidal movement whereas other species have been observed in the largest numbers when the tidal increases in speed. The tidal cycle has been observed to influence foraging rates at multiple tidal steam locations, both positively and negatively (Wade, 2015; Waggit et al., 2016; Goldsmith, 2017; Lieber et al., 2019). These results have also been observed during surveys of tidal stream devices with significant relationships between abundance estimates and tidal strength observed (Robbins, 2012; Savidge et al., 2014; Long, 2017; Envirosphere, 2018).

Furness et al. (2012) used a vulnerability index similar to ones used in offshore windfarms (Garthe & Hüppop, 2004) to investigate which species are most vulnerable to collision in Scottish waters. By assessing the species conservation status via four parameters (status in relation to the Birds Directive, percentage of the biogeographic population that occurs in Scotland, adult survival rate, and UK threat status) and seven biological parameters (drowning risk, mean and maximum diving depth, benthic foraging, use of tidal races for foraging, feeding range, disturbance by ship traffic, and habitat specialisation) a metric of impact was determined. In conclusion, the paper identified Black Guillemot, Razorbill, European Shag, Common Guillemot, Great Cormorant, divers and Atlantic Puffin as the species most vulnerable to the adverse effects from tidal turbines in Scottish waters. The method used within this study could be applied to other areas to provide site specific vulnerability estimates once initial surveys have ascertained which species are present.

5.2.4. Summary of current knowledge

This section provides an overview of the empirical evidence from tidal stream devices and summarises the results for the monitoring approaches described above for seabirds (see Table 4 for a summary of all monitoring techniques to date).

Currently there is little actual monitoring data or limited direct evidence relating to collision risk between birds and turbine devices and as such there is a large gap in current understanding of actual encounter rates as well as direct and indirect mortality rates in the event of a collision. From visual surveys to date, there is some evidence that seabird species (particularly cormorants and divers) do not habitually forage during periods of the fastest currents, with a clear preference for areas/times of a lower tidal flow. Some smaller species like auks have been observed to increase at tidal flow increase, at different locations. This highlights the importance of site-specific baseline surveys to address this. If the tidal patterns show a decrease in usage with an increase in current speed it would restrict the number of seabirds that are active when the devices would be operational.

The evidence gathered to date, indicating birds show distribution shifts away from a device, suggested far-field avoidance. However, there has not been enough information on near-field evasion to provide an overall conclusion. The monitoring undertaken for these projects/studies has provided useful insights into animal movements within the vicinity of tidal turbines and have proven the potential applicability of several technologies. Telemetry is widely used in ornithological studies, but there do not appear to be any published studies where data telemetry devices (either GPS or underwater accelerometers) have been deployed on seabirds close to tidal stream devices. Such studies would provide important empirical data.

Overall there is no evidence of an observed collision between a seabird and a tidal stream device. However, this may be due to the limitations associated with all monitoring methods and the limited amount of monitoring that has been undertaken. As direct collision is very hard to monitor for small species like seabirds, data are few and far between. The use of hydroacoustic devices provides the clearest “picture” to date. Hydroacoustic devices have tracked diving seabirds in the vicinity of a device (Williamson et al., 2015). Neither of the locations in which this monitoring has been successfully deployed have recorded a collision event, with very few encounters recorded.

The largest gap within our current understanding is driven by the lack of empirical avoidance data. Distribution shifts of several seabird species after the deployment of a device have been observed, but due to the challenges of monitoring direct collision, there is still unknown potential for collision, especially when considering arrays of devices.

5.3. Fish

Several studies have been undertaken evaluating the impact of tidal turbine devices on fish behaviour and fish collision risk with rotating turbine blades. This has included in situ monitoring, in laboratory settings and through collision risk modelling. A synthesis of current understanding of fish collision risk with tidal stream devices is provided below and within the evidence spreadsheet.

Within the UK, migratory fish have been highlighted as the main concern in regards to fish interactions with tidal stream devices. However, various fish species also contribute to the diet of diving seabirds and marine mammals.

The review has therefore considered all fish species (for which evidence exists) including commercially important species and those that are protected through environmental designations. Physical injuries to fish caused by mechanical strike, shear and cavitation are the principle risks identified.

5.3.1. Monitoring approaches

Monitoring to understand the potential collision risk of fish and elasmobranchs with tidal stream devices is in its infancy and there is limited data available to inform collision risk assessments. Direct sampling of fish (typically undertaken by nets and trawls) is impractical in the energetic conditions in which most tidal stream developments are placed and is therefore not an acceptable form of monitoring (Fraser et al., 2018). Currently monitoring has been undertaken through two main approaches:

- The first approach uses underwater video monitoring to assess fish distributions and monitor the device to ascertain potential rate of collision or the consequences of collision; and
- The second approach uses a hydroacoustic device to determine the spatial-temporal overlap between fish and the tidal stream device, and therefore the likelihood of encounters.

These methods can be used to enable an estimation of fish density. In addition, fish behaviour such as shoaling, avoidance and collision with turbines can be recorded. Underwater video monitoring can also allow species identification.

Underwater video techniques involve the placement of a camera system on the turbine structure. Video cameras can be used to record the presence of particular fish species in the vicinity of the turbine, information on tidally-induced behaviour and, to some degree, the passage of species through the turbine device to capture any collision or injury. One key limitation of video systems is that due to light requirements they are only able to capture data during daylight hours. Additionally, the field of view may not cover the entire rotor and the camera view can be obscured at times by the turbine blades meaning that not all encounters may be captured. Cameras may also become obscured by biofouling. Footage collected can provide clear evidence of collision or injury caused to fish, however, data analysis is extremely time consuming. The use of baited video cameras may provide additional information on species present but also risks biasing recording towards predatory species.

Echosounders, split-beam acoustic transducers (SBT), high definition sonar or other similar hydroacoustic devices can also be used to monitor fish presence in the vicinity of turbine devices. The deployment of such acoustic devices has varied between studies.

Echosounders can be mounted on a vessel to conduct transects across the development area. Specific over-the-turbine transects are necessary to generate a representative strike risk model but transects can also be conducted across the wider area to assess fish populations and diurnal movement patterns. Data collection through this mechanism is limited by vessel operational periods and weather down-time which might prevent data collection.

Hydroacoustic devices can also be placed directly onto the turbine device and left in situ for a set period of time or can be seabed-mounted and deployed within the wake of the tidal stream turbine. This fixed-location method includes the use of Dual Frequency IDentification SONar (DIDSON) acoustic cameras (Sound Metrics Corp., Seattle, WA), which can provide acoustic imagery to monitor movements of fish within the vicinity of tidal turbines. As devices can be continuously recording they can collect data across a 24-hour window and are not light sensitive so are able to monitor during the dark and in highly turbid environments. However, data analysis is resource intensive.

The placement, observational window and frequency of recording vary between studies but will result in a trade-off between data resolution and field of data capture. Only echosounder instruments with a sufficient range provide the practical means to investigate the behaviour of fish throughout the entire water column of a typical tidal channel. The functionality of echosounders in energetic environments has so far been limited due to the operational difficulties of data collection in such conditions and the intense interference caused by backscatter related to turbulence (Fraser et al., 2018).

Two additional techniques which have been trialled to assess fish collision risk are injury assessment (direct sampling of fish injuries) and fish tagging (tracking studies of fish movements), however, their accuracy and reliability to assess risk are inconclusive.

Direct sampling can be undertaken to conduct an injury assessment. During site visits, fish can be collected and any injured fish identified. The type of injury, such as bruising, laceration or descaling, can be identified and the likely cause assessed. In addition, discussions with fishermen can also provide data to inform injury assessment if they have noted any injured fish during catches. However, to date many assessments have been unable to conclude the sources of injury or determine if all injuries have come from a single source.

Attaching tracking tags to fish, is another method which has been used to analyse fish movements in the vicinity of tidal turbines. The use of tags can, for example, allow the tracking of seasonal and diurnal movements of fish species. It can also provide information on swimming velocity and direction and has been highlighted as particularly useful in areas with migratory fish species. The use of this method is relatively new and in many cases data is not yet publicly available. One of the main challenges faced in detecting acoustically tagged fish is poor receiver efficiency due to excessive noise interference when current speeds exceed 2 m s-1 (Redden et al., 2014). To date, such methods have had limited success in informing collision risk.

Use of electro-mechanical (strain/ accelerometers) devices can be used to measure force on a turbine blade from object collision and assess where on a turbine the collision has occurred. However, due to the nature of tidal stream environments accelerometers are always under strain and there is uncertainty over the sensitivity of the devices and the force of impact required to register a collision event. Currently these devices have not been utilised for fish collision risk monitoring and there is no clear evidence as to their effectiveness, however there is potential applicability for their use in monitoring basking shark collisions.

Despite the availability of the above monitoring techniques, it should be noted that many developments have not undertaken project specific monitoring and instead rely on desk-based reviews and historic data to inform the potential distribution of fish species in the vicinity of a site. Although the literature can identify potential species present in the vicinity of a tidal device and provide background on fish behaviour, the specific impacts through collision risk are difficult to predict. This is a significant limitation with respect to the current understanding of fish collision risk assessments.

5.3.2. Monitoring studies and results

Since the first in situ placing of a tidal turbine several developers have implemented monitoring to record fish species in the vicinity of tidal devices. Multiple approaches, as discussed above, have been used for monitoring potential collision risk, with varying degrees of success. This section reviews some of the monitoring undertaken across a range of developments, summarises the findings of the monitoring with regards to collision risk and discusses any limitations of the findings.

Ocean Renewable Power Company (ORPC), as part of their RivGen project, similarly used underwater imagery to assess fish distributions in the vicinity of their turbines in the Igiugig River, Alaska. Underwater imagery was collected 24 hours per day from 19 to 25 July and 19 to 27 August 2015 (Priest and Nemeth, 2015). Due to the large time and resource implications of analysing the video footage initial analysis focused on only the first 10 minutes of the footage each hour.

The initial results identified 1,020 fish from six species observed across the monitoring period. Several instances of fish moving through the turbine were recorded but there was no direct evidence of physical injury or collision. However, the footage did record some evidence of disorientation by juvenile salmon moving downstream (Priest and Nemeth, 2015). Following later analysis of the remaining footage results revealed a total 2,538 fish within the vicinity of the turbine. Across the period a total of 20 collisions were recorded (0.8 %), the majority of which involved shoals of juvenile fish (Matzner et al., 2017). The differences in results shows the limitation in only part assessing video footage and indicate the time constraints required to undertake accurate analysis. Additionally, the method of post processing and analysis of footage can be key in determining collision risk.

As part of the TidGen Project, ORPC undertook a down-looking hydroacoustic survey to assess the impact of their TidGen horizontal axis turbines. The survey was undertaken between August 2012 and September 2013, monitoring fish presence, abundance and vertical distribution. Key species recorded in the vicinity of the turbines at all tidal conditions were Atlantic herring, Atlantic mackerel, winter flounder, silver hake, haddock and white hake. The results of the study showed a significant decline in fish density closer to the turbine, starting from approximately 140 m from the device. Fish were more likely to be recorded at the same depth as the turbine during the night compared to day time, the tidal stage did not appear to have an impact. On the basis of this level of avoidance from the turbine it was concluded that the probability of a fish encountering the turbine’s blade would be less than 2.9%, based on the density of fish in the study area (Shen et al., 2015; FORCE, 2018). However, it should be noted that the use of hydroacoustics limited the ability to isolate individual fish species within mixed shoals and limited the area/ range in which behaviour could be observed.

The Cape Sharp Tidal project in Minas Passage, Canada, also utilised a downward facing hydroacoustic echosounder mounted onto a vessel as part of the baseline fish monitoring. The OpenHydro open centred turbine was deployed between 2009 and 2010 and 2016 and 2018. As part of defining the environmental baseline a fish-monitoring programme was implemented. Three 24-hour surveys in May, August and October 2016 were undertaken to assess fish abundance and behaviour. Following the start of operations four additional 24 hour surveys were undertaken in November 2016, January, March and May 2017. Preliminary findings suggested no significant effect of the turbine on the density of fish in the mid-field i.e. less than 1 km from the turbine or on fish vertical distributions or at different tidal states. However, monitoring did record highly variable fish densities seasonally with highest densities observed in November and January. Specific over-the-turbine transects were necessary to generate a representative strike risk model.

A further project example in which fish interaction with tidal stream devices have been examined through the use of hydroacoustic devices is the Ocean Renewables turbine testing platform in Cobscook Bay, Maine. In this example, two DIDSON acoustic cameras were deployed for a period of 22 hours in September 2010 (Viehman and Zydlewski, 2015). This time span included approximately 11 hours of daylight and 11 hours of darkness, and nearly two tidal cycles. The two DIDSON units were mounted upstream and downstream of the device and were operated in high-frequency mode (1.8 MHz), which provides better resolution at short ranges, however this limits the viewing window to 10 m. Behaviours of individual fish and schools were classified (e.g. entering, avoiding, passing, or remaining in the wake of the turbine) and the effects of turbine motion (rotating or not rotating), diel condition (day or night), and fish size (small, ≤10 cm; large, >10 cm) were analysed.

Turbine motion significantly affected the probability of fish entering, avoiding, and passing by the turbine. The turbine began rotating (and generating power) when current speeds exceeded 1 m s^{-1}. 11,377 fish were detected while the turbine was not rotating (24% of the time), and 17,611 were detected while it was rotating (76% of the time). When the turbine was rotating, the probability of fish entering the turbine decreased by over 35% from when it was not. The probability of fish entering the turbine was also greater at night. Overall, no direct collisions were detected, but 19% of fish were recorded entering the turbine while the turbine was operational and therefore at risk of collision. The largest shortcoming of the DIDSON technology in this study was the resolution, although DIDSON image resolution is among the best available, the results could not provide information on direct blade strike of fish or the condition of fish exiting the turbine for the same reason. Additionally, the rotation of the turbine caused a slight blurring around the blade edges, so everything within approximately 5 cm of the blades was not discernible (Viehman and Zydlewski, 2015).

Verdant at Roosevelt Island Tidal Energy (RITE) project used acoustic sampling via mobile split-beam acoustic transducers (SBT) to monitor fish. SBTs were attached and mounted downward on a vessel. Four baseline surveys were conducted between September 2005 and November 2005, six further surveys were undertaken during operation between October and December 2008. Additionally, 24 stationary SBTs were deployed to monitor passing fish. These were monitored once a month for the first six months of deployment, January to June 2007. From the stationary SBTs 38 schools and 82 individual fish were observed within the 112 minutes of video footage collected when turbines were rotating and operational. Thorough assessment of the footage revealed five occurrences (4%) of what appeared to be direct encounters with the rotor blade. However, a key limitation of the analysis was the limited field of view of the SBT which was blocked by turbine blades, as such some collision incidences may have been missed (Bevelhimer et al., 2016).

FORCE in the upper Bay of Fundy is a tidal energy test facility. A multi-year fish tracking study (2010-2013) has been undertaken at this site to address questions related to the potential risks of turbine operation to migratory species. VEMCO animal tracking technology was used to detect near year-round animal movements (path, velocity and depth) and behaviour of 386 tagged Atlantic salmon, Atlantic sturgeon, American eel and striped bass.

Hydo-acoustic receivers were placed in lines at 300 to 400 m intervals across both the Minas Passage (5 km wide) and the FORCE test site (1 km wide) to detect the presence of transmitters surgically implanted in fish as they moved within the Minas Passage during migrations into and out of the Minas Basin. Results show that the FORCE test area represents an important migratory corridor for all fish species examined and provided evidence of frequent use of the passage rather than use for just in- and out-migration. Compared to the other species monitored, striped bass were within the detection range of acoustic receivers for surprisingly long periods of time (up to 10 months) and were considered at significant risk of interaction with tidal devices.

Despite these findings, the results of the tagging study could not indicate direct interactions with tidal devices and therefore provides no assessment of collision risk. Additionally, the study found poor receiver detection efficiency during periods of high current velocity (greater than 2 m s-1). The tag transmission dataset was therefore predicted to represent 40% or less of the actual transmissions within the general range of the receivers which was a key limitation to the assessment (Redden et al., 2014).

As an additional part of this project specific fish injury monitoring was also undertaken. Incidence of injured fish were monitored through visits and discussions with fishers of the southern Minas Basin. The survey was conducted from May 2017 until approximately two weeks after the tidal turbine was removed. However, the cause of the injuries could not be determined, nor could it be concluded that all injuries were from a single source and therefore the assessment could not provide specific results on fish collision rates (FORCE, 2018).

5.3.3. Wider evidence and assessment of collision

Potential impacts of tidal turbines on fish species have been predicted through collision risk modelling. Various types of models have been used to predict the risk of fish colliding with tidal turbine devices as there is currently no single recommended model type for this purpose. As such studies have adopted different approaches to collision risk modelling. The different collision risk models have some similarities but differ in scope (coverage of the collision risk pathway) and in consideration of animal behaviour, such as natural seasonal or diurnal movement patterns, movement in different tidal flows and avoidance capacity.

Two of the key models which are used to directly assess collision risk include kinematic models which are mathematical models that describe the motion of objects without consideration of forces, this includes fish movement and tidal turbine operation; and Agent-Based Models (ABM) which simulate animal-structure interactions to predict collision risk.

A Kinetic Hydropower System (KHPS)-Fish Interaction Model was developed and applied by Verdant Power to support assessment of its Gen4 KHPS device at the RITE project. Using the results from acoustic fish monitoring surveys undertaken between 2007 and 2009 collision risk modelling was undertaken using Echoview analysis. Data on the location of 34,708 fish was used including the location, heading and velocity of each fish that passed through the multibeam field, alongside data on turbine operation and velocity, current velocity and tidal state (ebb/flow). The model predicted the probability of a blade strike on fish passing the turbine to be below 0.50 % for all arrays up to 30 turbines (Bevelhimer et al., 2016). However, the rotational speed of the turbine blades was also considered as a known constant at 35 ft s-1, the model did therefore not include parameters to assess the varying rotational speed at different points along the blade and therefore did not account for where on the blade the strike would occur. The blade was considered to be rotating above 1 m s-1 and all collision with a rotating blade were considered to be lethal.

To further assess the impacts of its TidGen device, Ocean Renewable Power conducted an encounter probability model to assess the likely number of fish collisions. The model was based on previous monitoring work at both the RivGen and TidGen test sites. The model took account of fish abundance, vertical distribution and avoidance behaviour (Shen et al., 2015). From the baseline monitoring it was assessed that the probability of fish being at the depth of the blade and therefore at risk of collision was 0.793 %. However, when accounting for avoidance behaviour and for time when the turbine was actually operational (minimum tidal current of > 1 m s-1) the probability of a collision fell to 0.083%. One caveat to this finding is that no interpretation has been made as to the impact on wider fish population dynamics and no specification is made as to what probability means, i.e. per day, per year, or based of fish density.

The probability of collision risk calculated in the above model differs from that determined as part of a separate operational monitoring study undertaken at the TidGen site. Based on the outputs of the monitoring study the probability of a fish encountering the turbine's blade was calculated to be less than 2.9 %, a 34-fold difference in collision probability (Viehman and Zydlewski, 2015; FORCE, 2018). This indicates the potential limitations of modelling (also noting all the potential inaccuracies associated with monitoring) and shows that care needs to be taken when interpreting results. However, the probability of collision from this model is comparable to the results from modelling by Bevelhimer et al. (2016), which predicted a 0.5 % risk for fish passing through the swept area of a 30-turbine array. No further assessment of the exposure time of fish to turbines was undertaken to analyse wider population impacts.

An ABM was developed to predict the likely collision risk of migrating silver eels passing a tidal turbine in Strangford Lough. The ABM aimed to simulate interactions between fish and consider the natural population cycle and behaviours. The dimensions of the device, the number of blades, current speed and the size of the fish were all characterised within the model. An additional parameter was also included where combined collision speeds greater than 5 m s-1 were assumed to be fatal.

Results predicted low rates of collisions, with just 1.1 % of eels passing through Strangford Lough predicted to collide with the turbines. The model also predicted that more collisions would occur for fish swimming upstream (against the flow and increased with longer body lengths). However, risk decreased the faster the fish swam. As with other modelling studies this project did not include an assessment of avoidance behaviour and therefore further work could include modifying swimming behaviours to include active turbine avoidance (Rossington and Benson, 2019).

The current outputs of collision risk models are primarily derived from density data indicating utilisation of fish at a set location. However, a recognised limitation is that these models do not generally account for avoidance behaviour of fish and thus it is difficult to assess the level of exposure to collision risk pressure. Modelling approaches are also limited by the degree of species, site and tidal device specific data for any given location. In addition, there is relatively little validation data of actual collisions to verify predictions that are made. Care therefore needs to be taken when interpreting the results from modelling studies as specific input parameters may mean results are not comparable to real world situations, as shown by Shen et al., (2015). However, modelling can provide an indication of likely collision risk when monitoring data is not available.

Alongside gathering of empirical data from locations in which tidal stream devices have been deployed, theoretical studies have also been undertaken to help understand collision risk. These studies look at fish activity to determine the likelihood of encounter based on behaviour alone. Interaction with turbine devices is only considered conceptually and not through direct interaction with tidal stream devices.

A study by Hammar et al. (2015), for example, assessed collision risk based upon video data of fish movements in strong tidal currents. Only fish species known to fully or partly utilise the mid and upper parts of the water column were included in the study as they were considered most important in the context of collision risk. Fish movements (directions, depth, speed), fish length, avoidance behaviour and tidal current were included in the analysis.

The study generated three important findings regarding the probability of co-occurrence between fish and tidal turbines. Firstly, results showed that as current speed increased fish movement decreased as fish seek shelter. Fish were very rare in currents as strong as 1 m s−1, therefore many species will have a very low probability of co-occurring with operating tidal turbines. Secondly, the findings indicate that in strong tidal currents fish are most likely to swim in the direction of the current, increasing the probability of entering turbines in the direction of the flow. The authors also noted that large fish have a higher probability of collision compared to small fish, including high probabilities of blade incident and damage.

Hammar et al. (2015) further assessed the implications of turbine design on likely collision impact and noted that turbine design has a large influence on potential mortality rates. The theoretical assessment found that small turbines were easier to avoid than large ones, and slow rotational speeds reduce the probability of turbine injury. Turbines with rotors moving fast and of a large diameter were more likely to cause severe injury. Among the many developing turbine designs, the Minesto Deep Green design is distinguished by the fact that it moves very fast (>10 m s-1) has a very large diameter and can operate in relatively slow currents (1 m s−1) where fish activity is higher than in stronger currents. The study suggested that the installation of such turbines in areas frequented by large fish of vulnerable populations should therefore be carefully assessed with regards to ecological risks before installation (Hammar et al., 2015).

Another factor which is not generally well understood is the survivability of fish following a collision. Combining strike probability with strike mortality provides a measure of turbine passage survival. As such a multi-year study was initiated by EPRI to evaluate the importance of turbine design, including leading-edge blade thickness, shape, and impact velocity, on fish survival (EPRI, 2011).

The study used modelling and laboratory testing to develop a blade design criterion. Initially the modelling indicated that a semi-circular shaped blade created the highest differential forces (leading edge pressures) and therefore had the greatest potential to deflect a fish prior to impact. Laboratory testing was undertaken using rainbow trout, white sturgeon and American eel, of various lengths to test the model findings. Turbines were installed in a large, recirculating flume and fish were exposed to blades of differing thicknesses (9.5, 25.4, 50.8, 101.6, and 152.4 mm) traveling at speeds up to 30 ft s-1.

The ratio of fish length to blade thickness (L/t) was used to standardize the results. Strike survival rates greater than 90% were observed when the L/t ratio was 1 or less (i.e., fish length was equivalent to or greater than the leading-edge blade thickness).

A similar study by Amaral et al. (2015) considered the survivability of fish following a collision by monitoring delayed mortality to fish injured during a collision. Underwater video cameras were used to record fish movements in the flume, and to test survivability of species for up to 48 hours following collision.

The results found that survivability was variable between species but ranged from 1 to 0.96 one-hour post collision. However, for some species survivability dropped 48 hour post testing, ranging from 1 to 0.91. The predominant form of injury observed was bruising (seen on 23% of all fish). This assessment therefore highlights the potential indirect/ delayed mortality related to collisions something which is not captured in current turbine monitoring studies (Amaral et al., 2015).

In both studies, across the species monitored the observed survival rates were generally greater than 95%. However, it should be noted that survivability decreases with increasing blade diameter (as blades are moving across a larger volume of water) and with increasing strike speed (Hammar et al., 2015). Survivability also varied between species. It should also be noted that due to the scale of the projects, full size turbines could not be used. In the study by Amaral et al., (2015) only a turbine with 1.5 m blade diameter could be used, which may have resulted in fewer injuries to fish.

5.3.4. Summary of current knowledge

Monitoring techniques utilised to monitor fish populations predominantly include either underwater video assessment or use of hydroacoustic devices (including Echosounders, SBTs, DIDSON). However, there are multiple limitations to the monitoring methods currently undertaken (see Table 4 for a summary of all monitoring techniques to date).

For hydroacoustic devices these limitations include a narrow sampling/ viewing window limiting the area of analysis, a limited resolution which makes estimating fish species and fish size particularly difficult and being unable to provide information of direct blade strike on fish or the condition of fish exiting the turbine. In contrast, video equipment allows for the identification of individual fish species and for the effects of turbines on swimming behaviour to be analysed. However, video cameras are not able to sample at night without artificial lighting, and often footage is obstructed by turbine blades which reduces the accuracy of the data collected.

Overall, Viehman and Zydlewski, (2015) concluded that if blade strike is the focus of a study, video may be a more useful tool, but that DIDSON is a useful tool for monitoring fish interaction with tidal turbine devices and is especially well suited to sampling at night or in turbid conditions.

Currently there is little actual monitoring data or limited direct evidence relating to collision risk between fish and turbine devices and as such there is a large gap in current understanding of actual encounter rates as well as direct and indirect mortality rates in the event of a collision. Fish species composition and abundance vary spatially between different tidal stream project sites, and temporally over seasonal or diurnal cycles, which means site specific studies over an appropriate timescale are, necessary to assess potential device impact. The potential interactions between fish and tidal turbines have been identified as a research gap for tidal stream power generation in the UK as a whole, and Wales in particular (Roche et al., 2016).

Limitations to current collision risk assessment include:

1. Uncertainly around all input parameters and models which do not include fish avoidance behaviour;
2. Limited analysis of individual species - behaviours of species, e.g. demersal vs pelagic or fish size, will change likely impacts and risk of collision;
3. Results are species, location and device specific and may not be appropriate for the assessment of other devices;
4. Delayed mortality from injury caused during collision has not been assessed. Survivability predicted from current studies are likely an underestimate; and
5. No interpretation as to what impact the probability of collision risk has on wider fish population dynamics.

Additionally, there has been little verification of model outputs and the associated predictions given the lack of available monitoring data and the limitations around this.

These limitations lead to uncertainty concerning the reliability of results and limit the potential extrapolation or use of results to inform other tidal developments. Therefore, care should be taken when interpreting results from previous studies.

Table 4: Summary table of the collision risk monitoring techniques used to date.

Monitoring Technique	Category of Monitoring	Receptor Monitored	Main Pros	Main Cons	*In situ* example(s)
Visual observations - vantage point	Spatial-temporal overlap	Marine mammals and seabirds	• Relatively cheap compared to the other observations allowing a longer-term evidence base to be collected; • Provides information on behaviour and occupancy patterns (surface only)	• Does not provide information on sub-surface collision risk; • Restricted to daylight monitoring; • Long-term datasets may be needed to undertake robust analysis; • Can be hard to provide accurate spatial information.	• All sites/projects to date have undertaken visual observations.
Visual observations - boat and aerial surveys	Spatial-temporal overlap	Marine mammals and seabirds	• Able to cover a large area quickly (aerial); • Only methods able to provide density estimates for modelling (true density provided over the whole site).	• Does not provide information on collision; • Restricted to daylight monitoring; • Can be hard to identify all animals to species (some stay at species group level).	• All sites/projects to date have undertaken visual observations.

Monitoring Technique	Category of Monitoring	Receptor Monitored	Main Pros	Main Cons	*In situ* example(s)
Device mounted video camera(s)	Direct collision and spatial-temporal overlap	Marine mammals, seabirds and fish	• Allows direct visual observation of any collisions; • Provides data on near-field presence and behaviours around turbines • Able to have multiple cameras on tidal stream device; • Technology is cheap.	• Quantity of data generated, associated processing and storage issues; • Specific environmental conditions required to allow visual observations to be made (i.e. during daytime, low turbid conditions); • Not usually viewed live, not able to stop any collision.	• Nova Innovation's devices in Bluemull Sound; • Sustainable Marine Energy's PLAT-I devices.
Passive Acoustic Monitoring (PAM)	Spatial-temporal overlap	Marine mammals	• Provide 24/7 monitoring; • Relatively easy to deploy and retrieve (if not attached to device).	• Only monitors cetaceans; • May not provide directional information; • Does not provide information on actual collision.	• Minesto (at the Holyhead Deep Site and Strangford Lough) • FORCE

Monitoring Technique	Category of Monitoring	Receptor Monitored	Main Pros	Main Cons	*In situ* example(s)
Active SONAR	Direct collision and spatial-temporal overlap	Marine mammals, seabirds and fish	• Provide real time feedback which could stop a collision from occurring; • Tracks 3D movement of animals.	• Large initial cost; • Not able to determine species for fish, seabirds or some mammal species; • Produces vast amounts of data which can be challenging to process/store.	• DeltaStream device in Ramsey Sound; • SeaGen in Strangford Lock.
Blade mounted pressure gauges/ accelerometers	Direct collision	Marine mammals, seabirds and fish	• Can provide operational performance data at same time as environmental.	• Not able to ascertain what has hit (maybe debris); • Inbuilt to turbines so hard to repair if broken; • Often hypersensitive and recording water flows.	• Several devices at EMEC.

Monitoring Technique	Category of Monitoring	Receptor Monitored	Main Pros	Main Cons	*In situ* example(s)
Animal-attached technology (GPS/accelerometers/ magnetometry)	Direct collision and spatial-temporal overlap.	Marine mammals and seabirds (and fish)	• Provides a large amount of data within a small tag, which can last a long time.	• May not be able to retrieve device (may not be needed by some type of device); • Provides an individual level of detail, may not be applicable to the population and therefore need to tag a lot to understand patterns fully. • May be limited information on near-field behaviour	• Seal population of Strangford Loch. • Seals within Ramsey Sound. • Seabirds off north coast of Anglesey.

6. Gap Analysis

Given the small number of tidal stream deployments to date and therefore the limited evidence base, a gap analysis of the evidence has been undertaken to determine the information that is required to undertake robust assessments of collision risk and also the best approach for future consenting.

The results of the gap analysis are presented in Table 5. In summary, the evidence that can be collected from baseline surveys to determine the spatial and temporal distribution and density estimates of marine mammals and seabirds is considered to be largely adequate, although it should be noted that not all tidal stream developments have undertaken baseline monitoring. Gathering this same spatial and temporal information for fish can be more challenging as most monitoring methods are based only on passage data and are dependent on the swimming behaviour or life history of particular fish species.

The key evidence gaps for all receptor groups during operational monitoring are in relation to determining avoidance or encounter rates of different marine species, as well as confirming if an actual collision has occurred and what the effects of a collision are. For example, there is evidence that some fish may avoid high tidal flows and thus not be exposed to collision risk and evidence that marine mammals may also avoid tidal turbines to some extent. Evidence on near-field evasion is also very limited thus creating challenges in estimating avoidance rates. For example, there is no evidence of what happens when fish approach tidal devices as a result of the pressure differential associated with turbine blades. Operational monitoring of fish is additionally challenging given the limitations of the particular methods that are available and that approaches are not species specific.

In addition to these gaps, the limited monitoring data that is currently available is species, location and device specific and may therefore not be transferable or applicable to the assessment of other tidal stream projects. In particular, species composition and abundance can vary spatially between different tidal stream project sites, and temporally over seasonal or diurnal cycles, which means site specific studies over an appropriate timescale are necessary to be able to assess the potential impact of a device.

Another key gap is the potential implication of collision mortality at the population level. Whilst it might be possible to estimate the collision risk for an individual, understanding what the consequence might be for the population is challenging. Methods do exist to assess population level effects of tidal stream devices, and these have been applied to marine mammals and seabirds but there is no evidence that these have been applied for fish.

The cumulative effects of deploying multiple tidal devices and arrays in the marine environment is a further key uncertainty. This is particularly the case for marine species that travel large distances and that have the potential to overlap with more than one project site.

Table 5: Gap analysis of evidence available for undertaking robust collision risk assessments.

Receptor	Baseline Evidence	Operational Monitoring	Modelling
Marine Mammals	• Survey methods available for collecting general baseline (density) data but limited information available on finer scale behaviour within tidal stream areas (non-device and device areas); • Density estimates between acoustic and visual surveys can be significantly different, a multi-method approach to baseline collection would be beneficial.	• Uncertainty around avoidance rates and actual strikes; • No evidence of the effectiveness of accelerometers and these are generally not considered sufficiently sensitive to accurately register collision events (although the larger the animal the more effective this method is likely to be); • Real-time assessment of collision requires improved algorithms for identifying marine mammals approaching turbine blades.	• Currently based on hypothetical avoidance rates (no avoidance behaviour); avoidance rates need to be well defined in order for models to provide accurate collision estimates • Assumes that all collisions are fatal; better information required on the consequences of collision.

Receptor	Baseline Evidence	Operational Monitoring	Modelling
Seabirds	• Survey methods available for collecting general baseline (density) data but fine-scale distribution is hard to gather over large spatial scales using traditional methods (vantage point).	• Unknown near-field avoidance rates and subsequent consequences if an actual strike was to occur; • Currently near-field observation methods cannot identify seabird species, therefore unknown impact on the population; • Telemetry is widely used in ornithology, but there has been no published work on bird movement within tidal stream environments using this technology.	• Currently based on hypothetical avoidance rates (no avoidance behaviour); avoidance rates need to be well defined in order for models to provide accurate collision estimates • Currently assume that all collisions are fatal, better information required on consequences of collision.

Receptor	Baseline Evidence	Operational Monitoring	Modelling
Fish	• Baseline data collection is lacking, with few methods used to understand which species are present. Unknown best monitoring approach; • The period that fish spend within the vicinity of the tidal stream device, is not well understood, seasonally, temporally, or tidally driven variation; • The behaviour of basking sharks in high energy environments; is there a similar attraction observed within seabirds and marine mammals? • The extent to which devices, moorings and inter-array areas may act as fish aggregation devices; • Better understanding needed on the use of tidal stream areas by fish, including: – Migratory species pathways and behaviour; – Fish swimming behaviour – Swimming depth preference and avoidance capability.	• Probability of collision not related to wider population impacts; • Real-time assessment of collision not currently undertaken; • Additional information on specific species impact. Fish are currently classed assessed as a homogenous entity, but likely to be differences in exposure between demersal and pelagic species; • No assessment of impacts to fish from pressure differential across the blade, which may cause injury and/or mortality; • There is little information currently on the sublethal effects of collision.	• Currently based on hypothetical avoidance rates (no avoidance behaviour); avoidance rates need to be well defined in order for models to provide accurate collision estimates • No agreed approach for Collision Risk Modelling for fish species; • Modelling parameters do not currently account for pressure differential across the blade; • Rotational speeds at different points along the blade not assessed within models and all collisions are considered fatal.

7. Recommendations for Addressing Key Gaps

Recommendations on addressing the key gaps in data and information have been identified and are discussed below.

Further evidence on realistic animal densities and near field evasion is likely to be needed to generate robust avoidance rates. This is particularly important for marine mammals and fish which may swim through tidal arrays on each tide and thus regularly be exposed to collision risk.

While acoustic techniques for tracking fine scale behaviour of marine animals close to turbines have matured recently, they still require further development. Other relevant technologies, such as blade mounted pressure sensors for instance, also need to be explored and developed further in order to confirm if they are effective in determining a collision event. More information on the behaviour of animals in the presence of a turbine and on the physical consequences of a collision (with the blade or pressure differential) is also required to fully understand the potential for death or injury.

Development of and improvement to fish monitoring techniques is a key recommendation and research priority to improve the knowledge of fish behaviour within tidal stream areas. Further research is also needed to accurately determine fish behaviour around tidal turbine devices, as well as to detect and record collision events to quantify the occurrence and frequency of collisions.

There may be some relevant evidence or lessons that can be learned from other similar types of development that have the potential to result in a collision risk, notwithstanding that the design of these developments are different to tidal energy devices and therefore the actual collision risk would not be the same. For example, there is growing experience of applying collision risk modelling to seabirds in relation to offshore wind farms. There is also a good understanding of the impact of hydropower turbines on fish. Established projects with longer term monitoring programmes would provide some further insight into the interaction of different marine animals with moving structures in the marine environment and the likelihood of evasion. They would also provide evidence on the potential impact of pressure differentials which is currently lacking from the evidence available from tidal stream development.

Population Viability Analysis (PVA) methods are available to determine population level effects and these are often applied to marine mammals and seabirds and can be applied to fish too but this is not often done. Assessing the population level effects on all fish receptors is considered to be more challenging. Monitoring techniques are not species specific and stock assessment data against which to compare impacts is quite limited. Equivalent Adult Values (EAVs) are often used to assess population level fish impacts but there are limitations to this approach. For example, published EAV’s are highly variable and monitoring is not species specific. The requirement to improve our confidence in monitoring and assessing fish impacts is therefore key to a reliable assessment of the population level effects becoming possible.

8. Conclusions

A primary concern with tidal turbines is the risk of marine animal collision, however, there is a lack of clear evidence to illustrate how animals interact with the turbines and to what degree this represents a real risk. This is largely due to the uncertainties relating to the likelihood and potential effects of collision and the individual and population consequences of injury/mortality. The main approaches that are used to help determine the possible risk of collision are modelling tools, monitoring in the field and laboratory studies. This Evidence Review has undertaken an in-depth review of these approaches, focussing in particular on information from field monitoring, and the empirical evidence available from a number of planned and implemented tidal stream projects in the UK, Europe and North America.

The range of available monitoring techniques, and their strengths and weaknesses, are summarised in Table 4. Monitoring requirements will vary from site to site, but could include:

- Animal behaviour around turbine structures (e.g. can they detect turbines, do they avoid them, can they escape once detected etc.);
- Quantification of number of collisions and near misses (primarily dependent on accuracy of assumed or modelled impact);
- Outcome of animal collisions (e.g. injury/damage to animal, noting that where evidence is not available, collision is currently assumed to be fatal on a precautionary basis); and
- Identification of object/species types (to inform behaviour and impact studies).

The review found that field monitoring techniques used to determine the spatial and temporal overlap between a tidal stream device and marine animal, primarily to characterise the baseline environment (baseline monitoring) but also during the operational phase (impact monitoring), are valuable in determining the presence, distribution and likely vulnerability of species to tidal stream devices. They also provide density estimates that are a key input parameter for collision risk models. However, these types of surveys need to be carefully designed to ensure that the data collected is of sufficient spatial resolution (e.g. include depth distribution) and accounts for temporal variability (e.g. tidal cycle and seasonality).

To date, none of the monitoring studies on marine mammals and seabirds have recorded a direct collision with a tidal device; however, there are limitations with all of these studies (e.g. shut down clause, no analysis of all available data and/or no actual monitoring of direct collision) such that if a collision had occurred it may not have been detected. One of the monitoring studies undertaken on fish have recorded collisions with tidal turbines, particularly shoaling juvenile fish. There has been an overall paucity of monitoring data given that there have only been a small number of tidal devices deployed and monitored thus far. Despite this, the data that has been collected to date, provides valuable evidence on the behaviour (e.g. far-field avoidance) and likely overlap of different marine species around devices.

Fine-scale 3D movement data, through telemetry and hydroacoustic devices, have provided some initial evidence for near-field evasions. However, these methods are relatively costly and generate a considerable amount of data which require a large amount of time and resource to process and analyse. In addition to the challenges of monitoring in a tidal environment, not all these methods are able to provide conclusive evidence that an actual strike has occurred, and each method has different limitations that need to be taken account of in terms of the resolution and quality of the data that can be collected (e.g. battery capacity of telemetry tags, narrow sampling/viewing window of hydroacoustic devices, video footage not possible to collect at night or in turbid conditions etc.).

Modelling continues to be the most commonly used approach to assessing the risk of collision. There are a range of modelling tools available, each with different input parameter requirements (e.g. the physical characteristics of turbines, physical and behavioural characteristics of animals and local density estimates). Model assumptions are often conservative, for example, they may assume there is no avoidance behaviour and that all collisions are fatal. The three main types of model available to determine the potential collision rate in marine mammals and seabirds (and which could also be used modified for fish) are ERMs, CRMs and ETPMs. Existing fish collision risk models include kinematic models and agent-based models.

From a review of the evidence currently available, there has been limited validation of collision risk models with the results of monitoring during operation. The level of confidence in the outputs of these modelling tools is therefore quite limited.

Over time, as additional tidal stream energy devices are deployed and monitored, the evidence base that can then be used in the consenting of future projects will increase. The monitoring techniques and ultimately the predictions of collision and its potential effects on the population will therefore also improve.

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10. Appendices

Appendix A - Agreed List of Tidal Devices

Table 6: Initial long list of tidal stream energy devices/developers agreed with NRW and the status of the monitoring and/or reporting.

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
Wales	Minesto	Deep Green Tidal Kite DG500 One 0.5 MW tidal kite, no moving parts.	Holyhead Deep	Off Holyhead, Anglesey, Wales	Testing in Strangford Lough 2017 and then deployment in Holyhead in 2018.	EIA undertaken. Currently undertaking operational monitoring. Monitoring a condition of Marine Licence (ORML 1618).	Yes
Wales	Tidal Energy Ltd.	DeltaStream 400 kW device of 3-bladed turbines	N/A	Ramsey Sound, Pembrokeshire, Wales	Operational March – December 2016.	Operational monitoring occurred and scientific papers of the results published. Company no longer exists so no contact was made.	Yes

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
Wales	Morlais	Multiple Consent application is being prepared for the demonstration zone	West Anglesey Demonstration Zone	Off Holyhead, Anglesey Wales	At the pre-consent phase.	EIA undertaken with baseline data collected, but no device has been put into operation and therefore no operational monitoring.	Yes
Wales	SIMEC Atlantis Energy	Up to nine Atlantis Resource SeaGen devices	Skerries Tidal Stream Array	Between Carmel Head and the Skerries, off Anglesey, Wales.	Consented in 2015. Project put on hold in 2016.	EIA undertaken, baseline data collected but no operational monitoring, as project has stalled.	No
Scotland	Multiple	Multiple: Testing site in which multiple devices have been placed. Will review the monitoring at EMEC as well as individual projects if specific monitoring has occurred.	EMEC	Falls of Warness, Orkney, Scotland.	The DA opened in 2006, with the first device placed in the water in September 2007.	EMEC undertakes wildlife observations throughout the year alongside various projects. Multiple researchers have published papers in the area. Annual reports up to 2014 online.	Yes
Scotland	Nova Innovation	Nova M100 turbine Twin 4.5 m blades 100 kw	Shetland Tidal Array	Bluemull Sound, Shetland, Scotland	Two devices operational since 2016 with an additional device deployed in 2017.	Non-statutory environmental assessment undertaken, including collision risk modelling. Monitoring started in 2010 and is continuing. Undertook phone interview for additional information.	Yes

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
Scotland	SIMEC Atlantis Energy	Atlantis Resources AR1500 and Andritz Hydro Hammerfest (AHH) AH1000 MK1. Four No.1.5 MW three 18 m blade turbines, one Atlantis and three AHH	MeyGen	Between Scotland's northernmost coast and Stroma.	Currently in Phase 1 with first turbine installed in October 2016, up to 4 *in situ* (by April 2018). Additional phases are planned with more turbines consented.	EIA undertaken. Currently undertaking operational monitoring. No information was found about this project. Atlantis did not partake in the evidence review.	Yes
Scotland	Nautricity	CoRMaT tidal stream turbine Contra-rotating turbine with two blades moving in opposite directions.	Argyll Tidal Demonstrator Project	Mull of Kintyre, Scotland	Approved in 2013 but never installed. Device installed at EMEC in 2017 (see EMEC above).	Environmental Appraisal for Mull of Kintyre site, using baseline data. No operational phase monitoring undertaken at this location. See EMEC, for monitoring at that location.	No
Scotland	DP Energy	Multiple	West Islay Tidal Project	West of Islay, Scotland.	Consented in 2017 by Crown Estate and Marine Scotland but no device has been placed in the water.	EIA undertaken, baseline data collected but no operational monitoring as project has halted.	No

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
Ireland	SIMEC Atlantis Energy	SeaGen 1.2 MW device with 2 No.600 kW powertrains	Strangford Narrows	Strangford Lough Narrows, Northern Ireland.	Operational from 2008-2016. Decommissioned in 2019.	Large amounts of monitoring data were collected and reported as part of this project.	Yes
Ireland	SmartBay	Multiple Ireland's national marine and energy test and demonstration site.	SmartBay	Galway Bay, west of Ireland	Operational since 2006.	Operational monitoring is being undertaken as part of the licence conditions.	Yes
Ireland	Sustainable Energy Authority of Ireland (SEAI)	Multiple Demonstration area.	Atlantic Marine Energy Test Site	Annagh Head, west of Belmullet, Ireland	Fully consented in 2015 but yet to have devices put in place.	EIA undertaken with baseline data collected, but no device has been put into operation and therefore no monitoring. Will follow up with company as they put out a tender for monitoring services – may still be collecting data.	Yes
Canada	Atlantis Operations Canada Ltd. (a joint venture of Atlantis Resources Ltd. and Rio Fundo Ltd. (a DP Energy affiliate))	Atlantis Resources AR1500 Three No.1.5 MW three 18 m blade turbines	N/A	Minas Passage, Bay of Fundy, Canada (Fundy Ocean Research Center for Energy (FORCE))	Unclear when the device was put into the water.	FORCE undertakes monitoring reporting annually and reports on their environmental effects. Scientific publications have been undertaken at this location.	Yes

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
Canada	Cape Sharp Tidal (OpenHydro and Emera)	OpenHydro Open centred 2 MW turbine (16 m diameter)	N/A	FORCE	First device 2009 – 2010. Second device 2016 – 2018 until OpenHydro went into liquidation.	FORCE undertakes monitoring reporting annually and reports on their environmental effects. Scientific publications have been undertaken at this location.	Yes
Canada	DP Energy	Six Andrtiz Hammerfest Hydro (AHH) MK1 (up to 9 MW)	Uisce Tapa	FORCE	Post-consent. Will use Berth E and C at FORCE. Not yet in water.	FORCE undertakes monitoring reporting annually and reports on their environmental effects. Scientific publications have been undertaken at this location.	No
Canada	Sustainable Marine Energy Ltd and SCHOTTEL Hydro	PLAT-1 Floating platform with four SCHOTTEL SIT250 70 kW turbines	N/A	Grand Passage (between Long Island and Brier Island, in Digby County, Nova Scotia)	Operational Sep 2018 and June 2019 for phase 1 testing.	Operational monitoring occurred via video cameras.	Yes

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
Canada	Clean Current	Clean Current turbine 65 kW Horizontal axis bi-directional ducted turbine.	N/A	Race Rocks, Off Vancouver Island, Canada	Operational between 2005-2011	Environmental Monitoring Report produced after 1 year of operation. No information was found about this project. Archipelago (consultancy who undertook the monitoring) did not partake in the evidence review.	Yes
USA	Ocean Renewable Power Company	RivGen Tidal Turbines Horizontal Axis Turbines	Igiugig River Energy Project	Igiugig River, Alaska, USA.	Operational 2014-2015.	Monitoring reports on fish available using EyeSea, 43 hours detected 20 fish interactions with no injury.	Yes
USA	Ocean Renewable Power Company	TidGen Tidal Turbines Horizontal Axis Turbines (750 kW)	Cobscook Bay Tidal Energy Project	Cobscook Bay, part of the bigger Bay of Fundy, off the Maine coast, USA.	Operational 2012-2017.	Monitoring reports 2012-2016 are available online.	Yes

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
USA	Verdant Power	Gen4 Free Flow System Grid-connected demonstration array of six Kinetic Hydropower System (KHPS) 3-bladed turbines. Gen5 is being licensed at the moment – for deployment in 2020.	Roosevelt Island Tidal Energy (RITE) Project Demonstration	East Channel of East River - New York, NY, USA.	Operational 2006-2009 (9,000 hours of operation).	Operational monitoring occurred, specifically for fish.	Yes
Australia	Atlantis Resources	100 kW Aquanator™ device, a 150 kW AN-150™ (Nereus™ I) device, and a 400 kW AN-400™ (Nereus™ II) device where used over the projects lifespan.	San Remo Test Site	Newhaven Wharf, near San Remo, Victoria, Australia	Operational between 2006 and 2015	Tethys mentions “zero environmental impact” after two years of independent testing. No information was found about this project. Atlantis did not partake in the evidence review.	Yes
Australia	Tanax Energy	N/A	Clarence Strait Tidal Energy Project	Clarence Strait, Northern Territory, Australia	Still in the pre-consent planning stage.	Impact assessment undertaken with baseline data collection but no operational monitoring.	No

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
England	Sustainable Marine Energy Ltd	PLAT-0 Submerged platform with two turbines.	N/A	Off Yarmouth, IOW. Then EMEC.	Blank cell	Operational monitoring occurred at IOW and also continued at EMEC. See EMEC, for monitoring at that location.	Yes
England	Perpetuss and Isle of Wight Council	Multiple Demonstration area.	Perpetuus Tidal Energy Centre (PTEC)	Off St. Catherine's Point, IOW, England	Fully consented in 2016 by MMO however put on hold in 2017 due to financial concerns.	EIA undertaken with baseline data collected, but no device has been put into operation and therefore no operational monitoring.	No
Netherlands	Multiple	Multiple Dutch Marine Energy Centre (DMEC)	DMEC	Marsdiep between Den Helder and the Wadden island of Texel, Holland	Operates one test site, but only mentions one user.	Little information online with no clear monitoring plan. Only device mentioned also placed in EMEC (see EMEC above).	No
France	Sabella	D10-1000 Multiple 10 m blades (1 MW)	N/A	Between Brest and Ushant Island, France	Operational 2015-2016 and then again in 2018-present	Email communication confirmed video cameras where placed on device.	Yes
France	SEENEOH	Multiple – small scale devices can be tested in a riverine environment	N/A	Gironde Estuary, Bordeaux	Operational since 2016	No monitoring to date but plan for fish mortality studies. Undertook telephone interview to find out about project.	Yes

Country	Developer	Device	Project	Location	Status	Monitoring and Reporting	Included within this review?
South Korea	South Korean Government	Cross-flow Helical Turbine (1 MW)	Uldolmok Tidal Power Station	Uldolmok Strait in the Yellow Sea, at Jindo Island, South Jeolla, South Korea	Operational since 2009 and currently in use	No environmental assessment or monitoring has taken place.	No
Multiple countries	OpenHydro (a Naval Energies company)	OpenHyrdo Open centred	N/A	Off Brittany, France; Seattle, Washington, USA; EMEC; and FORCE	Operational between 2007 until 2018 (not continuous) when company went into liquidation.	OpenHydro undertook several EIAs due to the different locations that the device has been placed. Operational monitoring also occurred at several of the sites. Included fish, marine mammals and seabirds. See EMEC and FORCE, for monitoring at that location. Company no longer exists so no contact was made.	Yes

Appendix B - Full list of Contacted organisations

Table 7: Organisations contacted (same order as Appendix A) that have/had devices *in situ* or pre-consent stage.

Organisation Contacted	Response
Minesto	No response received.
SIMEC Atlantis Energy	No response received.
Morlais	Response received and interview undertaken.
EMEC	Response received and interview undertaken.
Nova Innovation	Response received and interview undertaken.
DP Energy	No response received.
SmartBay	No response received.
Atlantic Marine Energy Test Site	No response received.
Sustainable Marine Energy	Response received and interview undertaken.
Archipelago (undertook monitoring of Clean Current at Race Rocks)	No response received.
Ocean Renewable Power Company	No response received.
Verdant Power	No response received.
Sabella	Response received.
SEENEOH	Response received and interview undertaken.

Table 8: Organisations contacted (same order as Appendix A) that are involved in tidal energy.

Organisation Contacted	Response
AZTI	No response received.
Bangor University	Response received.
Edinburgh University	Response received.
FORCE	No response received.
Juno Energy	Response received and interview undertaken.
Marine Energy Wales	Response received.
Marine Power Solutions	No response received.
ORJIP	Response received.
Plymouth University	No response received.
ScotMER	No response received.
SEACAMS	Response received and interviews undertaken.
SMRU (and SMRU Consulting)	No response received.

Data Archive Appendix

The data archive contains:

[A] The final report in Microsoft Word and Adobe PDF formats.

Metadata for this project is publicly accessible through Natural Resources Wales' Library Catalogue https://libcat.naturalresources.wales (English Version) and https://catllyfr.cyfoethnaturiol.cymru (Welsh Version) by searching 'Dataset Titles'.

Further copies of this report are available from library@cyfoethnaturiolcymru.gov.uk