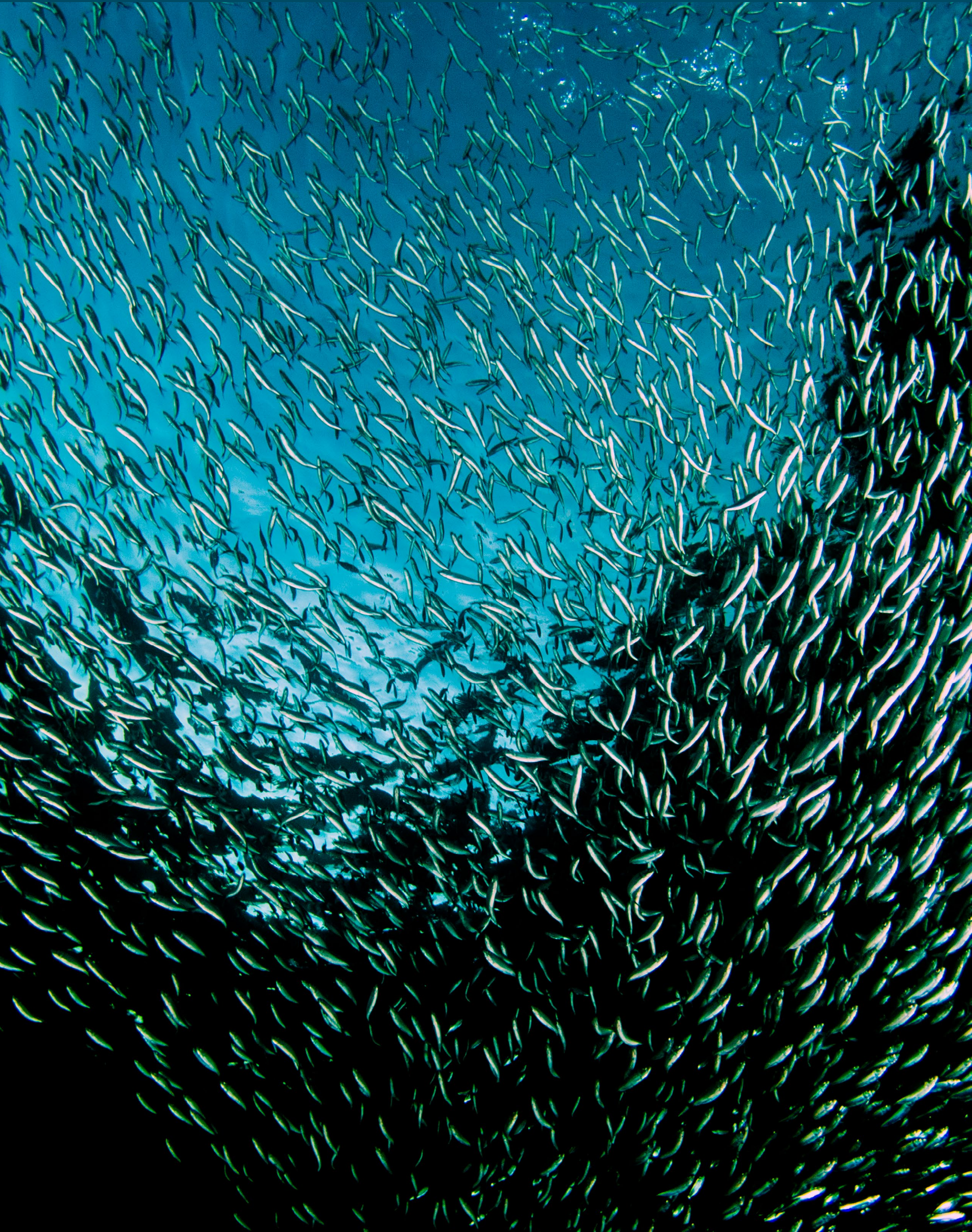

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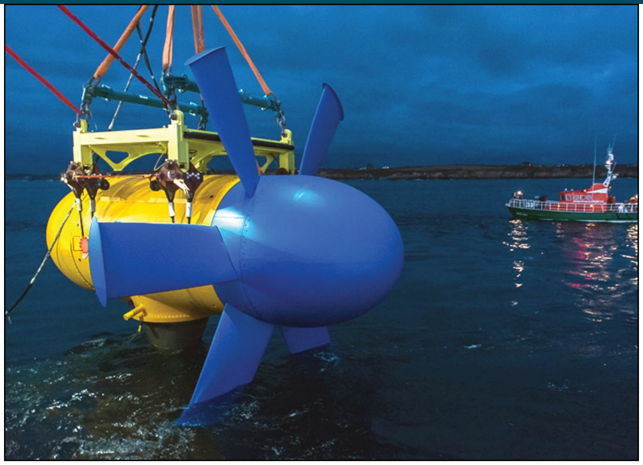

Chapter authors: Carol E. Sparling, Andrew C. Seitz, Elizabeth Masden, Kate Smith
Contributors: Natalie Isaksson, Hayley K. Farr

Collision Risk for Animals around Turbines

The potential for marine animals to encounter and collide with turbines, especially tidal and river turbines, along with the biological, ecological, and regulatory consequences of any such interactions, remain active areas of research and topics of global interest. Uncertainty and knowledge gaps associated with collision risk continue to present challenges within consenting/permitting (hereafter consenting) processes for turbine developments. Consequently, collision risk continues to be the focus of significant research effort, which in recent years has included environmental monitoring of operational devices and arrays. This chapter addresses the overall progress and growth in knowledge across this topic area, and specific progress related to marine mammals, fish, and seabirds.

There are additional risks to marine animals, particularly marine mammals and large fish species, related to collision with the vessels involved in the installation and maintenance of marine renewable energy (MRE) projects. However, this chapter focuses on risks from collision with the moving parts of MRE devices and systems.

3.1.
IMPORTANCE OF THE ISSUE

Collision risk is an issue that applies most directly to tidal and river energy conversion technologies (ORJIP Ocean Energy 2017). It relates to the moving components of devices (blades and rotors), as well as dynamic technologies, such as tidal kites or oscillating blades. Wave energy technologies are thought to be more benign with respect to collision risk because there are fewer submerged moving parts that have collision potential (Greaves et al. 2016). The potential risk to marine animals from interactions with the mooring and anchor lines of floating wave or tidal devices is addressed separately in Chapter 8 (Encounters of Marine Animals with Marine Renewable Energy Device Mooring Systems and Subsea Cables). The risk of birds colliding with wind turbines has been extensively studied, offering certain lessons that can be learned and applied to the risk of marine animals colliding with underwater turbines; these lessons are noted where pertinent.

Several factors contribute to the risk associated with the likelihood of animals colliding with turbine blades and the consequences of such collisions to the animal if a collision occurs. The factors that will affect this risk include the characteristics of the devices, animal behavior, and animal densities at the depth of the relevant moving parts of devices; these factors are explored throughout this chapter. The broad overlap between tidal and river resource areas and important habitats for fish, marine mammals, and seabirds (e.g., Benjamins et al. 2017; Macaulay et al. 2015; Staines et al. 2019; Viehman and Zydlewski 2017; Viehman et al. 2018; Waggitt et al. 2016) may increase the potential for encounters (Figure 3.1), including collisions. However, spatial and temporal patchiness in marine animal distribution, influenced by fine-scale hydrodynamics (at the scale of meters to a few hundred meters), could also influence encounter rates and collision risk (Lieber et al. 2018; Waggitt et al. 2017). The ecological significance of any collision events will depend on the physiological, population, and ecosystem consequences of any such interactions (Band et al. 2016).

Despite the potential for encounters and collisions, knowledge of actual risk is limited because the frequency of occurrence of these events (e.g., Copping et al. 2016; Furness et al. 2012) and their consequences are unknown. Detecting encounters or collision events or observing animal movement and behavior in relation to an underwater object (i.e., a turbine) is challenging. In the absence of empirical data, assumptions about how animals might avoid and evade turbines have been made based on lessons learned by the wind energy industry (Scottish Natural Heritage 2016). How an animal might perceive a tidal or river turbine and any associated risk is generally unknown, but information about visual fields and sensory biology may provide some insights into how species may be able to see or hear turbines (Band et al. 2016; Hansen et al. 2017; Hastie et al. 2018a; Martin and Wanless 2015; Martin et al. 2008; Nedelec et al. 2016; Popper and Hawkins 2018).

Many species of mammals, fish, and seabirds are subject to extensive legal protection globally: for example, in the United States (U.S.) they are protected by the Marine Mammal Protection Act (1972), Endangered Species Act (1973), and the Magnuson-Stevens Act (1976); in the European Union by the Habitats Directive (1992) and Birds Directive (2009); in Canada by the Species at Risk Act (2002) and Fisheries Act (1985); and in Australia by the Environment Protection and Biodiversity Act (1999). Further, many species of fish support subsistence, recreational, and commercial fisheries. The nations contributing to this report have invested significant effort in improving the management and movement of species back within safe biological limits (Hilborn 2020); but elsewhere (e.g., in developing economies) practices are reducing an increasing number of commercial stocks to unsustainable levels (FAO 2018). Under either practice, the increased mortality of these stocks is undesirable and undermines the sustainability of the species populations. Many seabird populations are already in decline and experiencing numerous pressures such as climate change, contamination, and fishing bycatch (Paleczny et al. 2015).

In general, where there is uncertainty about impacts, particularly in relation to protected species, regulatory processes in many jurisdictions currently follow the "precautionary principle" regarding the potential impacts and their consequences (Kreibel et al. 2001). In Europe and North America, precautionary regulatory approaches have led to conditions being placed on licenses, permits, and authorizations to reduce collision risk, such as through operational restrictions. Such conditions also commonly require developers to conduct post-installation monitoring that is focused on collision risk (Bennett et al. 2016). The purposes of such monitoring include validating the predictions of collision risk made in environmental impact assessments, and improving the knowledge about nearfield interactions between devices and marine wildlife. Monitoring is also commonly used to inform and enable regulators to adaptively manage tidal and river current projects.

Gaps in knowledge about collision risk and its consequences can therefore lead to conservative approaches in conducting environmental impact assessments and in implementing tidal energy developments (Le Lièvre and O'Hagan 2015; ORJIP Ocean Energy 2019). Although no evidence to date shows that direct interactions with tidal or river current energy technologies will cause measurable harm to individual marine animals or populations, collision risk remains a key issue for the future growth of the tidal and river current energy sector (Copping et al. 2017).

In general, aspects of this chapter that focus on collision risk in relation to marine mammals and seabirds are considered for tidal turbines, while collisions with fish may be applicable for freshwater river turbines or marine tidal turbines. Freshwater turbines may be referred to as river turbines or hydrokinetic turbines.

3.2.

SUMMARY OF KNOWLEDGE THROUGH 2016

In 2016, the state of the science for the risk of marine animal collision with MRE devices was in its infancy. Given the few deployed devices and considerable research challenges (e.g., difficulty working in dynamic tidal habitats or fast-flowing rivers, inability to monitor specific strike events, and a lack of a funding mechanisms to undertake strategic research and monitoring that might elucidate the problem), there was limited understanding of the nature of interactions between marine animals and MRE devices, including avoidance and evasion behaviors. Further, the understanding of the likely consequences of any occurrence of collision events, if they occurred, was limited.

No collisions had been observed around single turbines or small arrays prior to 2016, but collision remained a concern and it was one of the most challenging potential occurrences to monitor and observe. The *2016 State of the Science* report (Copping et al. 2016) identified the following key priorities related to collision risk for marine mammals, fish, and seabirds:

- development and refinement of methods to improve the understanding of species' spatial and temporal use of tidal habitat, species' behavior around operating devices and arrays, and the consequences of collision for both individuals and populations; and
- potential advancement of the science by benefiting from continued stakeholder engagement, adoption of an adaptive management approach, and standardization of the language used when describing collision risk, as well as species' avoidance and evasion behaviors.

Figure 3.1. Interactions of (from left to right) a harbor seal, a school of pollack, and a European shag with a non-operating tidal turbine. (Photo courtesy of Nova Innovation)

3.3.
DEFINITIONS

Researchers studying collision risk have created terminology to use in describing interactions, building off definitions provided in the *2016 State of the Science report*. These key definitions for collision risk are provided in Table 3.1.

Table 3. 1. Key terminology of relevance to collision risk between marine animals and MRE devices.

Term	Definition
Avoidance	Animals moving away from the area around an MRE device, at some distance from the object (ABPmer 2010; Wilson et al. 2007).
Collision	• Physical contact between marine animals and moving components of MRE devices, or with dynamically moving technologies. • Does not always imply injury (Amaral et al. 2015). • Includes pressure fields around blades (Wilson et al. 2007).
Collision rate	• Predicted rate of collisions between animals and moving components of MRE devices, or with dynamically moving technologies (Scottish Natural Heritage 2016). • Usually incorporates a correction factor for an “avoidance rate” to account for the assumed proportion of animals taking avoidance or evasive actions (Scottish Natural Heritage 2016), but does not take potential consequences into account.
Density at risk depth	• The density of animals at water depth likely to bring them into contact with relevant moving components of tidal or river turbines, or with dynamically moving technologies (Scottish Natural Heritage 2016). • For seabirds and marine mammals, usually calculated from surface densities from baseline surveys, with a correction factor applied.
Encounter	• To be in close proximity of a turbine. • May lead to a collision but only if the animal does not take appropriate avoidance or evasive action (Wilson et al. 2007).
Encounter rate	Predicted rate of animals and turbines occupying the same point in space and time (Scottish Natural Heritage 2016).
Evasion	Change in behavior to escape impact or contact with an MRE device at close range, analogous to swerving to prevent collision with an obstacle in the road (ABPmer 2010; Wilson et al. 2007).
Farfield	The area of ocean or bay around an MRE device, generally defined as more than five device diameters from the device or array of devices.
Nearfield	The localized area of sea occupied by and in very close proximity to an MRE device, generally considered to be within one to five device diameters.
Passive avoidance	To be swept clear of moving components of MRE devices, or dynamically moving technologies, by hydrodynamic forces (Scottish Natural Heritage 2016).
Post-installation or post-consent monitoring	• Monitoring carried out to gather data before devices are deployed (post-consent monitoring) or monitoring of the environmental effects of deployed MRE devices (post-installation monitoring). • Generally, either required by regulators to validate predictions made in environmental assessments or to provide an evidence base for adaptive management of effects for which there is residual uncertainty.
Sublethal collisions	• Collisions between marine animals and moving parts of devices that result in injury rather than immediate death. • Might include blunt force trauma or concussion and such effects may cause secondary injury or death, or affect an animal’s future foraging success and ability to reproduce (Onoufriou et al. 2019). • Sublethal effects are likely to be extremely difficult to predict or measure.

3.4.
COLLISION RISK TO MARINE MAMMALS

Marine mammals are considered in many nations to be most at risk from collision with turbines, particularly as many marine mammal populations are under stress from other anthropogenic activities as well as effects of climate change (Fabry et al. 2008). Knowledge generated prior to and since 2016 about marine mammal collision is addressed, followed by what has been learned since 2016.

3.4.1.
SUMMARY OF KNOWLEDGE THROUGH 2016

As documented in the *2016 State of the Science* report, there was no evidence of direct interactions between marine mammals and tidal devices or that such interactions will cause harm to individuals or populations (Copping et al. 2016). While numerous collision risk models have been developed to predict the likelihood and consequences of collision for marine mammals (e.g., Band 2014; Wilson et al. 2007), the potential for collision will likely vary significantly with site-dependent characteristics such as location, water depth, and tidal velocity. Prior to publication of the *2016 State of the Science* report, the lack of data available from monitoring studies conducted around operational MRE devices significantly hampered our understanding of marine mammals interaction in the vicinity of MRE devices. Several projects were in various stages of development at the time the 2016 report was published (e.g., MeyGen, Inner Sound; Shetland Tidal Array, Bluemull Sound; DeltaStream, Ramsey Sound; Cobscook Bay, Maine). Therefore, at that time, the potential for collisions between marine mammals and tidal turbines remained a significant concern, and uncertainty in this area was causing barriers to the consenting of tidal projects worldwide.

3.4.2.
KNOWLEDGE GENERATED SINCE 2016

Baseline Studies

Studies have maintained a continuing focus on understanding marine mammal use of tidal environments. The results of these studies collectively demonstrate variability between sites and locations, making it difficult to make generalizations about marine mammal use of tidal sites.

Recent investigations into fine-scale harbor porpoise (*Phocoena phocoena*) density and the use of the water column at a variety of tidal sites in Scotland have provided substantial data about harbor porpoise depth distribution and underwater behavior in tidal rapids. These studies found a large degree of variation between sites (Macaulay et al. 2015, 2017). They also showed that the depth distribution of harbor porpoises was typically bimodal; porpoises spent time foraging at the surface or at depth, and spent less time at intermediate depths. This suggests that the depth of turbine placement may strongly influence collision risk. At the only site where measurements were taken at night (Kyle Rhea, Scotland), porpoises were more often located near the sea surface, highlighting the importance of understanding daily variation in species depth distribution to assure accurate prediction of collision risk (Macaulay et al. 2015). Benjamins et al. (2017) demonstrated that the distribution of harbor porpoises can vary in tidal habitats at very small spatial and temporal scales, such that collision risk estimated on the basis of wide-scale average densities may not reflect actual risk at any one specific site.

Seal-tagging studies in the United Kingdom (UK) have increased knowledge about the behavior of harbor and grey seals in tidal environments. In the narrow, tidal channel of Kyle Rhea on the west coast of Scotland, harbor seals (*Phoca vitulina*) are present between April and August, and they haul out during the ebb tide and spend a high proportion of their time during the flood tide actively foraging in the high current areas (Hastie et al. 2016). Another telemetry study (Joy et al. 2018) revealed that in the tidal currents of Strangford Narrows in Northern Ireland, harbor seals predominately swam against the prevailing current during both ebb and flood tides. Similarly, as reported by Band et al. (2016), harbor seals in the Pentland Firth predominately traveled slowly against the current. Similar to the seals at Kyle Rhea, not all seal dives were to the seabed and there was a proportion of mid-water diving. This behavior contrasts with previous studies where most seal diving was thought to be to the seabed. In contrast to the behavior of the Kyle Rhea harbor seals, which were distributed in high current areas on the flood tide, Lieber et al. (2018) reported that harbor seals and grey seals (*Halichoerus grypus*) in the Strangford Narrows were more likely to be distributed on the periphery of high current areas. However, this assertion was based on a limited sample of observations from a vessel conducting repeat line transect surveys over two days (one on a spring tide and one on a neap tide). Similar to the case presented above for harbor porpoises, these studies indicate a high degree of between-site variability in seal occurrence and behavior, making it difficult to generalize collision risk between sites. Studies of prey abundance might provide additional information about the presence of marine mammals around turbines, but no such studies have been undertaken to date.

Project- and Site-based Monitoring

MeyGen, Inner Sound, Pentland Firth, Scotland

The first turbines at the MeyGen tidal energy site were deployed in 2016 in the Inner Sound of Pentland Firth in Scotland (Figure 3.2). Four 1.5 MW turbines were installed during the 2016–2017 timeframe and, to date, the array has generated more than 15 GWh of energy for the grid. The project environmental monitoring plan (PEMP; Rollings et al. [2016]) associated with the turbine array was developed to understand collision risk; one of the main elements that required monitoring as a condition of consent was "collision/encounter interactions with the tidal turbines for diving birds, marine mammals and fish of conservation concern." The PEMP included two primary objectives:

- Detect and quantify potential avoidance and collision rates for harbor seals, and verify and improve the accuracy of collision/encounter rate models.
- Provide sufficient monitoring data for impact assessment to allow each subsequent stage of the development to proceed.

Although the principal objective of the PEMP was to monitor the presence of harbor seals, the technology deployed (video cameras, active and passive acoustic monitoring [PAM]) was capable of monitoring for other marine mammal species, including grey seals and harbor porpoises, as well as fish (e.g., Atlantic salmon [*Salmo salar*]) and diving seabirds (e.g., black guillemots [*Cepphus grylle*] and shags [*Phalacrocorax aristotelis*]).). The exact details of the sensor technologies are covered in Chapter 10 (Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines).

Figure 3.2. A MeyGen tidal turbine ready for deployment in the Inner Sound of Pentland Firth in Scotland. (Photo courtesy of SIMEC Atlantis Energy)

During the initial 322 days of data collection (October 2017 to September 2018), more than 740 million transient sounds were recorded on the PAM system. After post-processing and verification, 724 porpoise and 26 dolphin events had 10 or more clicks. The numbers of porpoise clicks per event varied considerably with a mean of 220 (95 percent confidence interval [CI] 31–979). Similarly, the durations of the events varied from 0.5 to more than 2700 seconds (95 percent CI 21–1200). It is likely that some of these events involved more than one animal. Monthly reports of cetacean detections and system operations were provided to MeyGen and the Scottish Government between October 2017 and January 2019. A key output of the PAM data analyses will be the temporal occurrence of porpoise and dolphins around the turbine and the three-dimensional (3D) locations of echolocation clicks in relation to the position and operational status of the turbine; these data are not yet available although ongoing analysis suggests evidence of avoidance at both a medium (tens of meters) and a fine-scale (meters) from the rotors.

In addition to activities associated with the MeyGen PEMP and as part of the Marine Mammal Scientific Support program at the Sea Mammal Research Unit (SMRU) (University of St Andrews, Scotland), a series of seal telemetry studies have been undertaken close to the area in which the MeyGen array is located. Prior to the deployment of the turbines, 24 harbor seals were tagged in the Inner Sound to quantify the movements of seals in a wider spatial context. The results from these tag deployments are presented by Hastie et al. (2018b). An additional 16 harbor seals were tagged between April 16 and 18, 2018, to provide data during the turbine operation phase. Of these tagged seals, 12 transmitted both location data and high-resolution dive data. From the tags deployed in 2018, 504 days of data were collected, which included 53,484 global positioning system (GPS) locations (i.e., a GPS fix obtained from the tag during a surfacing event). During this deployment, tagged seals spent approximately 12 percent of their time within the Inner Sound and approximately 0.001 percent within the whole MeyGen lease area. A total of four GPS locations were recorded within 100 m of a turbine and the closest GPS location was 35 m from a turbine. To assess the effects of the turbine installation on harbor seal distribution, the species' use of space before and after installation was quantified. In general, seal use of the area showed a pattern of reduced usage within the Inner Sound post-deployment compared to pre-deployment. Furthermore, seal usage within the Inner Sound was reduced during turbine operation relative to non-operation in the post-deployment phase (Onoufriou 2020; Palmer et al. 2019).

The MeyGen project team is currently collaborating with SMRU to deploy an integrated monitoring platform during the next phase of turbine installation at the MeyGen site (Project Stroma, previously known as MeyGen Phase 1b, comprises an additional two turbines) to add key data about seal behavior and encounter rates. For technical details about this monitoring platform, see Section 10.4.4. of this report.

Nova Innovation, Bluemull Sound, Shetland, Scotland
In 2014, Nova Innovation installed a 30 kW demonstration turbine in Bluemull Sound. This turbine was decommissioned in 2016 and was followed in the same year by the installation and commissioning of the world's first offshore tidal array, comprising two Nova M100 (100 kW) turbines. A third turbine was added in early 2017 and Tesla battery storage was added in 2018 (Figure 3.3).

Current plans, under the Enabling Future Arrays in Tidal (EnFAIT)[1] project, are to extend the array from three to six turbines during 2020 to 2021 to achieve a total rated capacity of 600 kW. Nova's Shetland Tidal Array is approximately 25 km from the Yell Sound Coast Special Area of Conservation (SAC) designated for harbor seal. The average foraging distance of harbor seals is

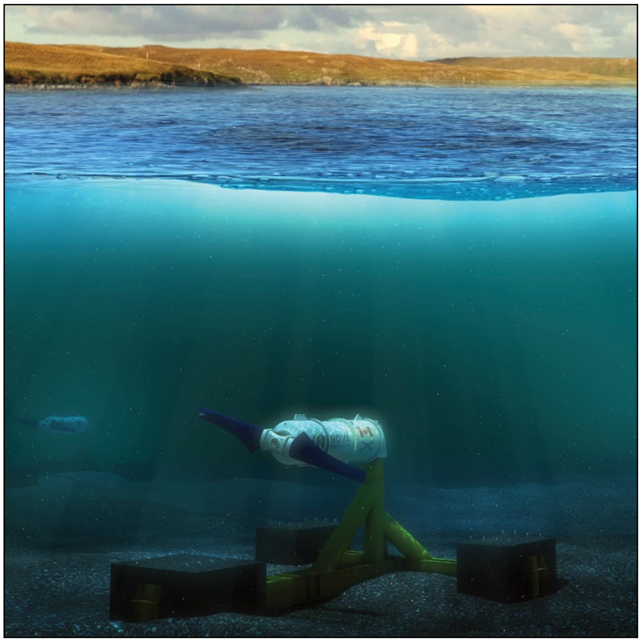

Figure 3.3. Nova Innovation's three-turbine tidal array in Bluemull Sound, Shetland, Scotland. (Photo courtesy of Nova Innovation)

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[1] *https://www.enfait.eu/*

30 to 50 km (Sharples et al. 2012), so animals associated with the SAC may forage within Bluemull Sound. The environmental assessment report for the six-turbine array[2] predicts that up to four harbor seal collisions per year may occur, assuming a 98 percent avoidance rate, based on the Encounter Risk Model detailed by the Scottish Natural Heritage (2016). Because this number was less than the potential biological removal (Wade 1998) for the relevant seal management unit (calculated to be 20 seals), regulatory and advisory bodies considered it to be acceptable, provided that appropriate monitoring was in place to validate these numbers.

The conditions of project licenses issued by Shetland Island Council and Marine Scotland require the environmental effects of the array to be monitored, as set forth in an environmental monitoring plan.[3] Land-based visual surveys of the site are carried out to gather information about the spatiotemporal distribution of marine mammals and birds in Bluemull Sound, and subsea video is used to monitor for potential collisions and nearfield interactions of marine animals with turbines. Land-based surveys that began in 2010 prior to the deployment of any turbines at the site, are still ongoing, and methodologies have recently been modified to focus on the turbine array area, rather than the wider Sound to gather information more specific to understanding collision risk. The approach is based on understanding site-use at different scales, to understand the likelihood of nearfield encounters between marine animals and turbines, as a descriptor of collision risk. Nearfield encounters are only possible if an animal uses the site. The likelihood increases if an animal uses the area immediately around the turbines and increases again if the animal actively swims or dives around the turbines during turbine operation.

Video monitoring uses three cameras per turbine, each attached to the nacelle (two directed toward the turbine rotor and one directed toward the seabed). The turbine is not illuminated, so video monitoring is only effective during daylight hours; water clarity at the site is generally very good and can be exceptional. The cameras record continuously but use a motion-detection system to automatically retain footage of potential wildlife-turbine interactions. A sub-sample of over 4000 hours of Nova's full 20,000+ hours of video footage have been examined and analyzed to date, representing approximately 20% of all footage recorded between October 2015 and March 2020. A combination of random and stratified sampling approaches was used to extract footage for analysis, to ensure coverage across the full tidal cycle, and times of presumed increased collision risk.

Eight mammal species (including Eurasian otter, *Lutra lutra*) have been recorded in land-based surveys, with grey seal, harbor seal and harbor porpoise the most frequently recorded (Nova Innovation 2020). Harbor porpoise were recorded in the area immediately around the turbines in 0.71% of scans, grey seal in 0.06% of scans and harbor seal in 0.32% of scans. For the nine years of survey data, the modeled probability of occurring within the area immediately around the turbines is < 0.02 for harbor porpoise and < 0.001 for both grey and harbor seals, indicating a very low turbine encounter risk for even the most commonly occurring marine mammals. Harbor seal is the only mammal species that has been observed in the subsea video footage analyzed to date. Thirteen instances of harbor seal have been observed, all during periods of slow tidal flow below the turbine cut-in speed, when the turbines were not operating. On one occasion, a harbor seal was observed actively pursuing fish around the base of the turbine. No physical contact between marine mammals and the turbine blades has been observed in any of the video footage to date (Nova Innovation 2020).

SeaGen Strangford Lough, Northern Ireland

There has been no new monitoring work at the SeaGen site since 2016 because the turbine (Figure 3.4) ceased to be operational in 2015 and was decommissioned in 2019. However, two scientific papers were published based on the outcomes of the monitoring program, which added to the knowledge base about collision risk. Sparling et al. (2018) presented the results of a seal telemetry study, which indicated that tagged seals transited less often and swam farther away from the turbine when it was operational than when it was not, and demonstrated that seals continued to use the narrows to transit through Strangford Lough with no overall change in their transit rates. This indicates that the turbine did not create a barrier effect, but that there was some degree of mid-range avoidance (of ~200 m). Joy et al. (2018) quantified the degree of local avoidance as a 68 percent reduction in seal use of the area within 200 m of the turbine. Building upon these results, Joy et al. (2018) demonstrated that taking this avoidance action indicates that a 90 percent

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[2] *https://www2.gov.scot/Topics/marine/Licensing/marine/scoping/NOVA-AdditionalTurbine/MLApp-022018/Ext-EA-Report*

[3] *https://www2.gov.scot/Topics/marine/Licensing/marine/scoping/nova*

Figure 3.4. The SeaGen tidal turbine when installed in Strangford Lough, Northern Ireland. (Photo courtesy of SIMEC Atlantis Energy)

reduction in collision risk is likely, compared to estimates derived from standard collision risk models.

DeltaStream, Ramsey Sound, Wales

At the time the *2016 State of the Science* report was published, the DeltaStream tidal energy device had been recently deployed in Ramsey Sound, Pembrokeshire, in Wales. The approach to monitoring was described but no data were presented. The turbine was deployed in December 2015 and remained operational until March 2016. The 12-channel hydrophone PAM system provided data (Malinka et al. 2018), while the Remote Acoustic Monitoring Platform, which had a multibeam sonar, produced no usable data. The PAM results indicated that the monitoring system successfully detected and localized porpoise and dolphin vocalizations over the three-month deployment period (Malinka et al. 2018). Porpoises and dolphins were detected, respectively, on 91.3 percent and 13.2 percent of the days during the monitoring period, and patterns of porpoise occurrence at the site could be linked to a range of covariates, such as tidal cycle, diurnal cycle, and season, which may be important when characterizing the risk of collision for devices at this location. Most of the encounters (71 percent of dolphin encounters and 91 percent of porpoise encounters) occurred during hours of darkness. Porpoises were detected across a wide range of flow rates, but detections were higher during ebb tide than during flood tide, higher during neap tides than spring tides, and lower at the highest rates of flow. The short period over which the monitoring was carried out limited analysis of porpoise behavior or their presence near the turbine. Analysis of tracks suggested that porpoises and dolphins were capable of detecting the structure and responding to it.

FORCE, Bay of Fundy, Nova Scotia, Canada

The Fundy Ocean Research Centre for Energy (FORCE) environmental effects monitoring program monitors effects at the FORCE test site outside the immediate vicinity of the devices with the initial understanding that developers with berth sites are responsible for monitoring close range effects around their own turbines. Monitoring using PAM to detect harbor porpoises within 200 to 1700 m of the site did not indicate any evidence of porpoise exclusion during the deployment or operation of Cape Sharp Tidal Venture's 16 m diameter 2 MW Open Hydro tidal turbine at Berth D (presence detected on 98.5 percent of the days monitored). However, click activity was significantly reduced at the C-PODs (i.e., PAM devices) closest to the turbine (200 to 230 m) and increased at the site 1700 m away, suggesting short-range acoustic effects on activity and spatial use by porpoises (Tollit et al. 2019). This suggests a reduction in potential collision risk relative to that assumed from baseline assessments.

Work is also under way at FORCE to establish an integrated, performance-tested sensor package that is accepted by regulators, for use by developers deploying equipment to monitor close range interactions, under a program named "The Pathway Program," in collaboration with the Offshore Energy Research Association and Nova Scotia Department of Energy and Mines. This program aims to provide a proven platform alongside automated data processing algorithms and software for analysis of passive and active acoustic data (see Chapter 10, Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines), which will provide important data for resolving uncertainties related to collision risk.

Sustainable Marine Energy, Grand Passage, Nova Scotia, Bay of Fundy, Canada

In late 2018, Sustainable Marine Energy (Canada) Ltd. (SME) deployed a floating tidal energy converter (PLAT-I), in Grand Passage, Canada. The project environmental effects monitoring plan is designed to provide information about underwater noise added to the marine environment by PLAT-I, and assess how marine animals respond to PLAT-I. Mitigation measures implemented during the deployment included daylight-only operation of turbines and halting turbine operation if species at risk were observed near the device. In addition, direct monitoring of the platform was required during all periods of turbine operation. This monitoring included video camera recording of each of the four operating turbines, recording of acoustic data over the full range of marine mammal vocalizations, and conducting marine animal observations at 30-minute intervals.

To meet these requirements, four video cameras were positioned facing downstream, each camera approximately centered on its associated rotor. The method provided an effective means of monitoring turbine rotors and assessing potential interactions with marine life, because visibility was generally good, light was sufficient, and suspended particles were few. An experienced third-party contractor conducted video analysis, which included screening representative samples for potential animal sightings and verifying or refuting potential sightings. Video quality was mainly rated as fair to good; inanimate materials such as seaweed and other debris were noted frequently. Aside from several observations of jellyfish, only one positive identification of marine life was made (a fish – smelt) (C. Chandler, personal communication).

Passive acoustic data collection was accomplished using a stationary icListen high-frequency hydrophone suspended beneath the PLAT-I hull. Ambient noise data indicated that turbine noise is below noise levels typically emitted by fishing and recreational vessels, so no hearing injury to fish or harbor porpoise would be expected.

Intermittent marine animal observations made either from onboard PLAT-I or from the control shore station resulted in no observations of marine animals within 500 m of the platform during the initial testing period (C. Chandler, personal communication).

Subsequent testing phases will incorporate learnings and expand research and development activities aimed at developing cost-effective environmental monitoring systems that will function effectively and reliably during future deployments.

Minesto: Strangford Lough, Northern Ireland and Holyhead Deep, Anglesey, Wales

Minesto UK has carried out a number of studies of the collision risk posed by their unique kite-design tidal energy generator. The collaborative, European Union (EU)-funded Powerkite[4] project collected environmental data (Kregting et al. 2018), and collision risk models were developed (Schmitt et al. 2017) and recently translated to an open-source game engine called Blender (*blender.org*). Simulations loosely based on the quarter-scale Minesto device indicated that there is a variable collision probability ranging from an inevitable collision if an animal passes at the position of the mooring point to the probability of collision decreasing with distance from the central mooring point (Schmitt et al. 2017). At the mean flight depth of the kite, the probability of collision is approximately 80 percent in the center of the kite trajectory, and more collisions are predicted to occur with the tether than with the kite itself.

Multibeam sonars were deployed around the Minesto quarter-scale device installed in Strangford Lough in Northern Ireland to (1) understand the spatiotemporal variability in seal and fish presence around the device and how it corresponds to fine-scale changes in hydrodynamics, and (2) collect evidence of nearfield subsurface behavior, including data about animal movement, depth, trajectories, and possible evasive behaviors (Lieber et al. 2017).

In addition to the Powerkite project, Minesto has also conducted simulation-based assessments of collision risk for consenting applications for their Strangford Lough and Holyhead Deep (Anglesey, Wales) projects. Booth et al. (2015) assessed collision probabilities for harbor seals in relation to the Strangford Lough deployment, based on their reported depth distributions. This work reported that the probability of a simulated animal coming into direct contact with the device varied depending on the anchor point of the device (surface or bottom-mounted) and the animal's swimming speed and behavior. Overall, collision probabilities varied between 0.05 percent and 8 percent depending on the conditions simulated. Booth et al. (2015) also assessed the consequences relative to population levels of a range of collision rates to provide context for the results of the collision probability modeling exercise. This allowed for an exploration of the level of collision risk that might be

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[4] *https://www.powerkite-project.eu/*

considered acceptable (i.e., not resulting in a significant impact on each population in the long term). For grey seals and harbor porpoises, very high encounter rates would be required to achieve collision rates that would be of concern at the population level (higher still if assuming some form of evasion). These encounter rates were considered to be beyond what one would reasonably expect to see at any site at the scale of this project. However, for bottlenose dolphins, based on the collision probabilities and population consequence assessment (assuming no evasion), even a single collision would be detrimental and therefore, effort was required to understand empirical encounter rates in the presence of the turbine for this species.

Minesto recently installed a Deep Green device (their 0.5 MW kite) at Holyhead Deep, Anglesey, in Wales (Figure 3.5). In 2019, a PAM system was developed in conjunction with the commissioning of the kite; further details of the system are provided in Chapter 10 (Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines). The objective was to monitor cetacean movement and investigate response around the operational kite. The species of interest were harbor porpoise and several dolphin species, in particular bottlenose dolphin (*Tursiops truncatus*) for which a single collision is estimated to cause population-level effects (G. Veneruso, personal communication).

Figure 3.5. Minesto's Deep Green 0.5 MW tidal kite being deployed at Holyhead Deep, in Anglesey, Wales. (Photo courtesy of Minesto)

Oosterschekering, Netherlands

The Oosterschekering, a storm surge barrier in the Netherlands, houses five integrated tidal turbines in an area where harbor porpoise, grey seals, and harbor seals are known to occur (Leopold and Scholl 2019). The surge barrier has been in place since 1986 and the turbines were installed in December 2015. Before the tidal turbines were installed, a small number of seals were tagged and shown to pass through the storm surge barrier, suggesting that it did not act as a physical barrier to their movement. It is not clear how the seals are traversing the storm surge barrier, however; their depth of passage and favored phase of the tides are not known. This lack of information makes it difficult to estimate the risk of collision.

Field Trials

Progress has been made in understanding the potential consequences of collision risk. Researchers at SMRU in Scotland have carried out a series of collision trials, using a vessel-mounted turbine blade and seal and porpoise carcasses to mimic blade strikes. Magnetic resonance imaging scans of carcasses after the trials demonstrated that significant skeletal damage occurs at speeds above 6 m/s (Onoufriou et al. 2019). Although tidal-stream velocities will seldom reach this speed, the speed of the blade tip may. Below these speeds, there was no evidence of skeletal trauma or obvious indicators of extensive soft-tissue damage, but because of the difficulties in assessing soft-tissue damage such as bruising and tissue edema in previously frozen carcasses, the soft-tissue assessments were not considered reliable indicators. Grear et al. (2018) tested two mechanical properties of harbor seal tissues to understand the ability of the skin and blubber to resist blunt force trauma. There were significant differences in responses between the test speeds and age of the animal, but not in the orientation of the tissue relative to the strike. Tissues were either frozen or fresh. In the case of the frozen tissue, an increase in stiffness and strength of the skin was found, but there was no conclusive trend in blubber material properties. They concluded that frozen tissue, especially skin, cannot serve as an accurate replacement for testing fresh material. It is also important to note that there has been no reliable assessment of the likelihood or consequence of concussion as a result of strike, which has the potential to be fatal (i.e., the animal loses consciousness and drowns).

The potential for marine mammals to hear tidal energy devices is an important concept related to understanding collision risk (Hastie et al. 2018a). The interactions are complex and depend on turbine source levels, ambient sound, propagation in moving water, sensory abilities, swim speeds, and diving behaviors. Empirical measurement of the noise emitted by turbines and the understanding of how noise propagates is one area in which progress has been made, as reviewed in detail in Chapter 4 (Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices). All indications from sites monitored to date are that marine mammals should detect tidal turbines acoustically and may use avoidance behaviors if they perceive the turbines to be a threat. Field playback studies using recordings of tidal turbines indicate responses at the scale of a few hundred meters, although the responses depend on the acoustic characteristics of the signal and the hearing sensitivity of the species (Hastie et al. 2018a; Robertson et al. 2018). Turbines that emit mostly low-frequency noise may not be audible at long ranges to high-frequency specialists such as harbor porpoises. Similarly, devices that emit more higher-frequency sound may not be audible to low-frequency hearing species. This highlights the need to take into account the turbine-specific acoustic footprint and the hearing capabilities of the species likely to be present. Predictive modeling of the acoustic energy output of new turbines prior to their deployment should inform the range at which marine animals may be able to hear devices and provide insight into the ability of animals to respond appropriately and avoid collision (Marmo 2017). However, the degree to which the audibility and "warning distance" actually influence behavior, and ultimately the risk of collision, is uncertain.

Modeling and Data Inputs

Since the publication of the *2016 State of the Science* report, considerable progress has been made in the area of collision risk modeling, including the development of modified models to quantify predictions of collision risk for non-horizontal-axis turbine designs (see the discussion by Booth et al. [2015] and Schmitt et al. [2017] above in relation to the Minesto device). Other examples include simulations that provide a framework to allow behavioral influences such as food availability and responses to noise to be incorporated, as was created for Ramsey Sound (Lake et al. 2017). A spatially explicit Individual-Based Modeling (IBM) approach is being developed at SMRU to explore the potential consequences of the impacts of MRE projects, including collision. However, this outcome is still at least a year away from completion (B. McConnell, personal communication). Given the complexity of behavioral responses and the need to understand collision risk at the array scale, the future of collision risk modeling is uncertain. As collision risk models are improved, field monitoring data will still be needed to validate predictive models.

Several studies have investigated the sensitivity of collision models to various input parameters. For example, Copping and Grear (2018) presented an analysis that incorporated a number of different parameters into a simple collision risk model, including variation in site-specific geography, tidal current, depth distribution of animals, and a prediction of the likely severity of collision. This analysis suggested that collisions leading to "serious injury" were likely to be relatively rare events but that the risk of serious injury varied between species and site and, in particular, in the degree of channel "blockage" created by turbines. Similarly, Band et al. (2016) demonstrated a reduction in predicted collision risk with sequential parameter refinements, which incorporated detailed information about seal behavior, depth distribution, turbine characteristics, severity of collision, etc. However, analyses such as these also indicate that predictions of risk are extremely sensitive to assumptions about behavioral parameters that can only be measured around operating turbines, parameters such as avoidance or fine-scale evasive responses. For instance, Joy et al. (2018), by incorporating empirical data collected around SeaGen (Sparling et al. 2018), recently demonstrated the effect of incorporating observed levels of avoidance of the turbine. As summarized in Section 3.4.2, collision risk estimates using empirical seal density estimates in the presence of the turbine were 90 percent lower than those estimated using data from before turbine installation, indicating an avoidance value of approximately 60 percent.

3.4.3.

RESEARCH AND MONITORING NEEDS TO RETIRE THE ISSUE

There are still a number of knowledge gaps and uncertainties in relation to the probability and consequences of collisions between marine mammals and tidal energy devices, including better understanding of the likelihood of collision with and avoidance of turbines, better understanding of the consequences of a collision with a turbine blade, translating individual collision risk to population-level risk, better understanding of the sublethal effects that may cause secondary injury or death, scaling of collision risk from a single turbine to arrays, and the need for collaboration among sectors to retire the risk of collision, as described in the following paragraphs.

Likelihood of collision with and avoidance of turbines by marine mammals – There are indications that some degree of "mid-range" avoidance exists at the scale of a few hundred meters around devices, and in response to playbacks (Hastie et al. 2018a; Joy et al. 2018; Sparling et al. 2018). However, information describing the occurrence and behavior of marine mammals at close range to devices (1–10s of meters) does not exist. The tools and technologies to allow this research to be conducted are being developed (Cotter et al. 2018; Gillespie et al. 2020; Hastie et al. 2019; Malinka et al. 2018; Sparling et al. 2016). Information about the equipment and techniques that contribute to determining collision risk and close encounters with animals and turbines can be found in Chapter 10 (Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines).

Consequences of collision with a turbine blade – Further work is needed to determine the consequence of a collision and how likely it is that a marine mammal will die as a result of the encounter. Indications are that this likelihood will vary with species, device type, speed of encounter, the body part struck, and the part of the device with which the animal collides (Copping and Grear 2018; Onoufriou et al. 2019).

Translating individual collision risk to population-level risk – There is a need to understand the potential population-level consequences of collision. If mortality rates can be determined from predicted collision rates, then it is straightforward to incorporate the latter as an additional source of mortality into traditional matrix population models to predict the future population trajectory of affected populations. These models must be dynamic to enable incorporation of a changing collision risk as the population size changes. Alternative approaches include comparison of predicted mortality rates to a calculated potential biological removal value (Wade 1998).

Sublethal effects – Effects that do not result in serious injury or death are difficult to predict or measure but could have serious consequences; for example, blunt force trauma or concussion could affect an animal's future foraging success and ability to reproduce. Techniques exist for incorporating sublethal effects into the prediction of future population consequences, but the necessary knowledge to carry out these analyses does not currently exist for collision risk and marine mammals. More information about (1) the occurrence and nature of the injuries, and (2) the links between injury and an individual's ability to survive and reproduce is needed for these analyses.

Scaling collision risk from a single turbine to arrays – With few devices in the water, insight into the potential risk to marine mammals from turbine blades cannot be well predicted as the industry moves toward larger commercial arrays. Among the challenges for scaling up the knowledge of collision risk from a single device would be whether animal responses to individual turbines might influence collision risk with other turbines in an array. Predictive models validated with collision risk data collected around single devices and small arrays may be useful to understanding the range of potential outcomes, identifying particular sensitivities, and directing future avenues of research. It may also be possible to directly incorporate array-scale predictive modeling into array design optimization, combining collision risk constraints with other optimization parameters.

Collaboration among sectors to retire the risk of collision – Collaborative approaches involving academia, industry, and government have been shown to be good models for determining the level of risk associated with collision and for enabling the development of a common understanding that can lead to risk retirement for collision. A number of academic/government/industry collaborations have been successful, including those associated with Ocean Energy Systems (OES)-Environmental for other stressors (as detailed in Chapter 13, Risk Retirement and Data Transferability for Marine Renewable Energy). However, retiring collision risk involves additional challenges beyond the technical challenges already noted. Issues of commercial confidentiality, project timelines, and budgetary constraints sometimes conflict with academic requirements, including open-source requirements, data sharing, and attitudes toward publishing. To address these challenges, funding sources need to have a degree of flexibility to respond to changing project timelines, and research institutions need to retain key expertise. There also needs to be a degree of external governance of monitoring and research programs to assure that maximum benefit is drawn for all stakeholders, and that objective and trusted science is delivered.

3.5.
COLLISION RISK TO FISH

Many species of fish have been considered to be at risk from collision with turbines in tidal and river environments. However, few empirical data were available before the *2016 State of the Science* report was written to assess the risk. A summary of what was known at that time is followed here by more recent findings.

3.5.1.
SUMMARY OF KNOWLEDGE THROUGH 2016

At the time the *2016 State of the Science* report was published, fish species were considered to be potentially at risk of collision with MRE devices. Results from several fish-turbine interaction tests in laboratory settings suggested high survival rates (>95 percent; Amaral et al. 2015; Castro-Santos and Haro 2015). Similarly, field studies were used to elucidate fish presence, avoidance, and evasion around MRE devices, but fish strikes had not been observed (Broadhurst et al. 2014; Hammar et al. 2013; Viehman and Zydlewski 2015). Substantial progress was made in the development of models that estimate the possibility of fish encountering MRE devices (Shen et al. 2015; Tomechik et al. 2015), the consequences of blade strike (Romero-Gomez and Richmond 2014), and the population-level ecological risks (Amaral et al. 2015; Hammar et al. 2015).

3.5.2.
KNOWLEDGE GENERATED SINCE 2016

Flume/Laboratory Studies

Three flume studies conducted since publication of the *2016 State of the Science* report were aimed at understanding certain aspects of the risk hydrokinetic turbines may pose to fishes, as well as understanding fishes' avoidance behavior around an operating turbine (Yoshida et al. 2020; Zhang et al. 2017) and the results of blade strike on fishes (Bevelhimer et al. 2019). To understand avoidance behavior, the ratios of turbine tip speed to fish size and swimming velocity were estimated for a proposed turbine in coastal Japan and were replicated in a scaled-down laboratory setting (Zhang et al. 2017). The passing rates, positions, and reactions of Japanese rice fish (*Oryzias latipes*) were recorded after upstream and downstream releases near an axial flow turbine in a rectangular swim flume, during which the flow velocity was held constant and the rotation frequency was varied. Based on the study results, Zhang et al. (2017) concluded that, similar to other flume and field studies, turbine operation significantly affected the avoidance behavior of fish, which increased as rotational frequency and tip speed increased. These behavioral alterations likely decrease collision risk for fishes in the wild and provide information for parameter estimation of numerical models aimed at further understanding fish behavior around turbines. The study results led the authors to recommend that hydrokinetic turbines with relatively high rotational frequencies be placed at the downstream end of a channel to minimize the collision risk to fishes. Currently, the feasibility of transferring these results to other fish taxa and turbine designs is unknown. Yoshida et al. (2020) similarly carried out a laboratory-scale water tank test to examine the behaviors of the ray-finned Tamoroko (*Gnathopogon elongatus*) around turbine blades rotated by a motor. A water current was applied to the flume as well. Although most fish passed outside the turbine blades throughout the duration of the experiment, when the current was added to the flume the behavior of the fish changed, resulting in approximately a one percent chance of collision with a blade. However, of two fish collisions observed, neither resulted in injury to the fish and both were thought to have occurred because the fish was affected by the current. Comparing with the results for Japanese rice fish (Zhang et al. 2017), the authors suggested that the ray-finned Tamoroko has a higher risk of collision despite its faster swimming speed (Yoshida et al. 2020). In addition, it appears that fishes capable of avoiding turbine blades without a current may be less capable of doing so when a current is running (Yoshida et al. 2020).

To understand the effects of blade strikes on fishes, three fish species (gizzard shad [*Dorosoma cepedianum*], rainbow trout [*Oncorhynchus mykiss*], and hybrid striped bass [*Morone saxatilus* x *M. chrysops*]) were exposed to simulated blade strikes in a laboratory setting (Bevelhimer et al. 2019). The relationships among blade thickness, impact velocity, and body orientation were examined to understand the relationships between turbine characteristics and the probability of injury and mortality of different fish species. Mid-body strikes resulted in the highest mortality, followed by head strikes, while tail strikes produced the lowest mortality. Lateral strikes caused greater mortality than dorsal and ventral strikes, and higher strike velocities and thinner blades contributed to increased mortality. Results such as these ultimately could be used to inform injury and mortality estimates of fish interacting with turbines and by turbine designers to modify designs to minimize the probability and impact of blade strike. Currently, there are no reports of such studies informing the design of turbines, but this is an important area to inform the evolution of future device designs.

Baseline Field Studies

Two baseline studies conducted since 2016 had a primary focus on understanding the presence/absence of fishes at two different sites—one in the Bay of Fundy, in Cobscook Bay, Maine (Viehman and Zydlewski 2017) and the other in Minas Passage, Nova Scotia (Viehman et al. 2018), while a third baseline study quantified how the distribution of fish schools overlaps with the operational depth and tidal current speeds used by tidal kites in the Irish Sea (Whitton et al. 2020). Investigators used different acoustic methods to examine fish presence/absence and vertical distribution, including single-beam and split-beam echosounders in Cobscook Bay, and an Acoustic Zooplankton and Fish Profiler (AZFP) in Minas Passage, while in the Irish Sea, both methods were used. In Cobscook Bay, data were continuously collected for two years at the proposed depth of an MRE turbine using a bottom-mounted, side-looking echosounder. From these data, fish counts were determined and temporal patterns in abundance were examined. In Minas Passage, data were collected during one month each in winter and summer by an upward-facing AZFP deployed at the FORCE test site. In the Irish Sea at the West Anglesey Demonstration Zone for tidal energy, AZFP data were collected for three months in late fall to winter, while split-beam echosounder data were collected and trawls were conducting for groundtruthing at the beginning and end of the AZFP data collection period. From these data, fish density, distribution, and overlap with a proposed hydrokinetic device were calculated in relation to one or more of the following: season, tide stage, diel stage, tidal current speeds, or suspended particulate matter.

In study locations in the Bay of Fundy and the Gulf of Maine where tidal turbines are proposed for deployment, fish abundance (quantified as counts and density) and vertical distribution varied with the season, diel stage, and tidal stage (Viehman and Zydlewski 2017; Viehman et al. 2018). In the Irish Sea, fish school diel vertical migrations were driven by depth of light penetration into the water column, which in turn is controlled by the supply of solar radiation and cross-sectional area of suspended particulate matter (Whitton et al. 2020). As a result, fish schools were found shallower in the morning and evening, and deeper in the middle of the day, with the fish at the deepest depths during lower current speeds corresponding with neap tides. When fish schools were present, they only overlapped with predicted kite operation depths 5% of the time, representing a mean of 6% of the potential kite operating time.

These baseline observations aid in understanding the potential collision risk of fishes and turbines. Because fish counts may be proportional to the encounter rate of fish with a turbine at the same depth, variable fish abundance and distribution in both studies indicate that the risk to fish is similarly variable (Viehman and Zydlewski 2017). Furthermore, the linkage between fish presence and environmental cycles may not be restricted to the locations mentioned in these studies, which could help refine the predictions of potential fish interactions at other tidal energy sites by using modeling exercises.

Deployed Support Structures and Turbines

Group Behavior

By extending the same methodologies and approaches used in pre-deployment baseline studies, installation and post-installation assessment of the impacts of support structures and turbines on fishes, such as avoidance behavior and encounter probability, can be inferred at a group level by observing multiple fish, such as shoals or even local populations. Specifically, comparisons of fish presence/absence, counts, or densities in locations where a turbine is deployed and in nearby reference locations (where a turbine is not deployed) can be made. Similar comparisons can be made before and after a support structure or turbine is deployed to infer the effects of turbines as part of post-consent monitoring programs.

One study examined the relative impacts of device installation vs. normal operation by using a Before-After-Control-Impact study design to compare an index of fish density close to and farther away from an MRE tidal energy device deployed in Cobscook Bay, Maine (Staines et al. 2019). The index consisted of mean volume backscattering strength obtained from 24-hour stationary, down-looking hydroacoustic surveys. These data were collected several times per year at an “impact” site close to an MRE device and at a control site farther away from the MRE device, both before and after turbine installation. One of the main findings was that the operational status of the installed turbine and on-water activity disturbances (e.g., industry vessel and diving activities) varied at the impact site and possibly influenced results. Specifically, lower fish densities were observed during installation and maintenance periods than during normal device operation. The authors emphasized the importance of timing device installation, maintenance and decommissioning to avoid major fish migrations or presence of endangered and threatened species (Staines et al. 2019).

One study was conducted to understand the aggregation characteristics of fishes around a turbine support structure in a high-energy tidal site near the Orkney Islands in Scotland (Fraser et al. 2018; Williamson et al. 2019). Using multifrequency echosounder data, the initial analysis found a large increase in fish-school numbers at the turbine site relative to a control site, which was inferred to be an attraction effect of the static support structure (Fraser et al. 2018). The second analysis used a predictive approach that relied on Generalized Additive Models, and found that the fish-school area and occupied depth around the static turbine support structure were significantly related to the time of day, current velocity, and tide stage (ebb/flood; Williamson et al. 2019). Both analyses found that there were more fish schools present at water velocities less than 1.0 m/s than at higher velocities, and there were more fish schools present near the turbine site than at the control site. From the results, it was inferred that the aggregation of prey fishes near turbine structures may increase prey availability and predator foraging efficiency, which may increase predator collision risk (Williamson et al. 2019). It was further inferred that the biggest change in the behavior of predatory fish would occur at night when they were predicted to occupy deeper waters, which may be manifested in energetics and collision risk, both of which may ultimately have effects at the population level. The investigators concluded that information about changes in fishes around turbine structures can be used to estimate the cumulative effects on predators at a population level, by incorporating observational results into ecosystem and population models. Lieber et al. (2019) also reported the presence of a predictable foraging hotspot for several tern species in the surface wake of the SeaGen device. Although no observations of marine mammals were reported, it is possible that predators could be attracted to such a hotspot, thereby increasing the potential for collision.

During the EnFAIT project in Bluemull Sound, Scotland, fish of the genus *Pollachius* (identified as saithe, *Pollachius virens*) were regularly observed in the subsea video footage (around 20-30% of footage analyzed to date— Nova Innovation 2020). The only other fish species observed in the footage was an individual long-spined scorpion fish (*Taurulus bubalis)* attached to one of the cameras lenses and an unidentified large species thought to be a dogfish, around the base of the turbine. The saithe usually occurred in groups of five or more individuals, often much larger. Individuals were generally seen around the nacelle and blades of the turbines at slack tide and the start of the flood and ebb, moving closer to the seabed or to the shelter created by the nacelle as tidal flow increased. Some exceptions were observed, with individual fish persisting in the vicinity of the nacelle and blades once the turbines started rotating. However, most fish observations corresponded to periods of slower flow speeds and no physical contact between fish and the turbine blades was ever observed in any of the footage.

To understand the aggregation characteristics of fishes near rotating turbines, hydroacoustic surveys were conducted in the East River, New York (Bevelhimer et al. 2017) and in Cobscook Bay, Maine (Grippo et al. 2017) to examine fish densities and distributions in relation to turbines. In both studies, the results suggest that rotating turbines elicit an avoidance response in fishes, even as far as 140 m from the device (Grippo et al. 2017). Collectively, these studies demonstrate that groups of fish show avoidance behavior relative to turbines on different time scales, indicating a reduced probability that fish will physically interact with a rotating device.

Individual Behavior of Fishes

To monitor the individual behavior of fishes near turbines, relatively fine-scale (centimeter to meter scale) information must be collected using cameras or acoustic imaging systems. In cases when individual behavior is being monitored, individual fish are identified and their reactions (or lack thereof) near a turbine are classified into different types, such as attraction or avoidance. Optical cameras provide relatively high-resolution information, but their use is limited by darkness or lack of water clarity. In contrast, acoustic imaging systems (i.e., BlueView, Dual-Frequency Identification Sonar [DIDSON], ARIS) can be used in darkness and low-clarity water, but they provide lower-resolution information than that of optical cameras, and species identification is not always possible.

In the relatively turbid East River of New York, DIDSON data collected in the vicinity of a bottom-mounted horizontal-axis turbine were analyzed to identify and understand individual fish swim tracks around a rotating horizontal-axis turbine (Bevelhimer et al. 2017). In contrast, in the Kvichak River in Alaska, which is relatively clear, optical cameras were used to document and understand fish behavior around a horizontal-axis helical turbine (Matzner et al. 2017). In general, individual fishes appeared to adjust their behavior around turbines. In the East River, some fish responded to the turbine by adjusting their swimming behavior, for example by making small adjustments in their swimming direction and velocity as they passed near the turbine, which can be termed evasion (Bevelhimer et al. 2017). Specifically, individual fishes that were headed toward rotating blades usually avoided the blades by reducing their swimming velocity, adjusting their horizontal swimming direction slightly, and angling away. In the Kvichak River, all adult fish demonstrated some type of avoidance reaction, as did the majority of juveniles; approximately one-third of juveniles passed through the turbine (Matzner et al. 2017).

This information about the behavior of individual fishes around rotating turbines can be scaled up to the group level by incorporating it into collective behavior models or individual-based models to improve the understanding of the impacts of turbines on populations (Shen et al. 2016). However, current field-based efforts to include such information are infrequent (Hammar et al. 2015; Staines et al. 2020) and, as such, real-world data to parameterize these behaviors in models are limited (Bevelhimer et al. 2017). Consequently, these two studies represent an important step toward understanding the behavior of individual fishes near rotating turbines.

Collisions between Turbines and Fishes

While most field-based research focuses on group-level and individual-level behavior around turbines, relatively little focuses on the frequency of actual collisions between turbines and fishes. This line of research is in its infancy, as demonstrated by the fact that no fish collision research was reviewed in the *2016 State of the Science* report. Since 2016, two projects have examined fish collisions with turbines (Bevelhimer et al. 2017; Matzner et al. 2017). Both research projects that examined the frequency of fish collisions relied on manual review of data, because automated detections and descriptions of collision events are currently not possible. In the East River, New York, potential collision events documented in DIDSON data collected in the vicinity of a bottom-mounted horizontal-axis turbine were identified through automated analyses (Bevelhimer et al. 2017). Subsequently, potential collision events were manually evaluated by examining the characteristics of those fish tracks to infer blade strikes. In the Kvichak River, Alaska, optical camera footage was visually examined for collision events (Matzner et al. 2017).

In both studies, collisions ranged from infrequent to nonexistent. In the East River, 36 individual tracks were identified as having the possibility of having had a close encounter with the turbine based on each fish's proximity to the turbine, but there were no observations of fish being struck by rotating blades in the video images that were obtained (Bevelhimer et al. 2017). In more than 42 hours of camera footage reviewed from the Kvichak River, there were only 20 potential contact interactions, of which only 3 were classified as "maybe" collisions after close visual examination (Matzner et al. 2017). On only one occasion was an actual contact confirmed, and it involved an adult fish that contacted the camera, not the turbine itself. More interactions with the turbine were detected at night, which the investigators hypothesized resulted from probable bias introduced by nighttime use of artificial light. The bias was speculated to exist because lights were thought to possibly attract fish and increase their detection probability as a result of the light being reflected from the fish itself (Matzner et al. 2017).

Modeling Studies

As a valuable complement to field-based studies, modeling studies have been conducted to understand several facets of potential impacts of hydrokinetic devices on fishes, including encounter risk, behavior, and collision risk. These models can fill information gaps when field studies are not feasible or lack the spatial or temporal resolution to answer important questions. In the past, many models did not incorporate empirical data (i.e., data collected in the field), but this is changing as research on turbines effects matures.

Encounter Risk

In the context of MRE devices, encounter risk is considered to be the probability that a fish spatially overlaps with different components of a hydrokinetic device (Viehman et al. 2018). These components can vary among studies and are typically predefined by investigators to address regulatory questions. To understand encounter risk, probabilistic models are used to determine the probability that a fish will occur in a predefined volume of water that corresponds to some component(s) of a turbine. Generally, these models rely on understanding horizontal and vertical fish distribution, the physical characteristics of the turbine site including water depth and bathymetric characteristics, and turbine characteristics including their placement in the environment and their dimensions. Encounter risk was modeled in two studies, one in Cobscook Bay, Maine (Shen et al. 2016) and one in Minas Passage, Nova Scotia (Viehman et al. 2018). In Cobscook Bay, a model used empirically collected echosounder data from stationary and mobile hydroacoustic surveys to examine the probability that fish would be at the depth of the turbine and could therefore encounter it as close as 10 m upstream (Shen et al. 2016). In Minas Passage, empirical fish density and vertical distribution data collected by an echosounder were used to estimate the probability of spatial overlap with the device under three fish distribution scenarios: (1) uniform vertical distribution; (2) winter vertical distribution; and (3) summer vertical distribution (Viehman et al. 2018).

In general, the probability of encounter is low and varies with the season, fish community, and turbine design. In Cobscook Bay, the maximum probability of a given fish encountering the whole device during a year was 0.432 (95 percent CI: [0.305, 0.553]), and the probability of a given fish encountering only device blades during a year was 0.058 (95 percent% CI: [0.043, 0.073]; Shen et al. 2016). In Minas Passage, the probability that fish would encounter the marine hydrokinetic device based on spatial overlap alone was 0.00175 with uniform vertical distribution (Viehman et al. 2018). The probability of encounter was 0.00064 for the winter vertical distribution of fish (median proportion of fish at turbine depth = 0.365), and 0.00099 for the summer vertical distribution (median proportion of fish at turbine depth = 0.566). These are likely conservative estimates of encounter probability because neither model incorporated the avoidance or evasion behaviors of fishes. If avoidance and evasion behaviors are considered, the encounter probability would likely be considerably lower.

Behavior of Fishes when Encountering a Turbine

The behavior of fishes when encountering a turbine has been explored in one study in an IBM framework

(Grippo et al. 2017). The goal of the study was to use empirical data to characterize the magnitude, ecological significance, and potential drivers of behavioral responses. To accomplish this, data from field surveys, hydrodynamic modeling, and behavioral simulations that described fish responses hundreds of meters upstream and downstream of the turbine were correlated to stimuli generated by the turbine, as well as currents in the environment. Fish behavior near the turbine was simulated in a relatively simple individual-based model (Eulerian-Lagrangian-Agent Method [ELAM]) and related to three potential stimuli generated by the turbine, including flow patterns, noise, and visual stimuli. Initial results indicated low impacts to fish (Grippo et al. 2017).

Collision Risk Modeling

Collision risk modeling is used to understand, predict, and assess potential rates of a fish either running into static components of a turbine or being struck by moving parts of the turbine (Xodus Group 2016). In general, collision risk models use a physical description of the turbine and characteristics of fishes such as body size, abundance, and swimming activity to estimate potential collision rates. To accomplish this, the models quantify how often the turbine parts will be in the same place at the same time as a fish. The occurrence of turbine parts will depend on the turbine size, architecture, and movement characteristics.

To understand collision risk for Atlantic salmon passing near the turbine site, four scenarios based on two project stages and two different types of turbines were considered (Xodus Group 2016). Turbine characteristics were taken from device-specific engineering information, whereas the sources of hydrodynamic and bathymetric characteristics were not described. Using a 95 percent avoidance rate for Atlantic salmon, which is based on previous research and is assumed to be precautionary (Scottish Natural Heritage 2016), and the worst-case scenario of an array consisting of 200 individual 10-bladed turbines, the collision risk for any given individual fish of a certain life stage that passes through the turbine site during its oceanic migratory circuit is expected to be 0.007 percent for grilse and adults, and 0.003 percent for smolts. Scenarios with fewer turbines and turbines with fewer blades produced lower collision risk estimates.

3.5.3.
RESEARCH AND MONITORING NEEDS TO RETIRE THE ISSUE

Additional research and monitoring, including field studies, modeling, and flume studies, can advance our understanding of the risks of fish collision with MRE and hydrokinetic devices. In addition, in many cases, the results from one approach can inform other approaches, such as field study results providing information for model validation and improvement. These studies should focus on all stages of MRE development, including the collection of baseline information and post-installation impacts on fishes. Because monitoring of and research on the potential impacts of turbines on fishes is a relatively new field, most of the recommendations are basic compared to other mature fields related to understanding anthropogenic impacts on organisms. Some of the priority needs for understanding collision risk for fishes with MRE devices are listed below.

Placement of MRE devices – The generalized recommendation, based upon flume research (Zhang et al. 2017), for placing MREs at the downstream end of a channel should be re-examined, because it is likely that placement recommendations will vary with location and fish species.

Groundtruthing acoustic targets – To determine which fish species are in the vicinity of MRE devices, acoustic targets should be groundtruthed for both baseline and post-installation research and monitoring that use acoustic methods (echosounders), which will lead to better understanding of fish distribution and behavior.

Individual fish behavior – Detailed information about the behavior of individual fishes should be collected to complement information gained from group-level observations to understand the ramifications of altered behavior (Bevelhimer et al. 2017) and to inform encounter probability and collision risk models. Once methodologies are refined, they can be used to answer behavioral questions that have eluded researchers. Because echosounders (e.g., split-beam sonar) have not been particularly effective in sampling nearfield areas, once a fish gets close to a turbine, this method is less helpful than cameras for determining the extent and outcomes of interactions. Even with cameras, identifying collision versus avoidance at close distances remains problematic (Matzner et al. 2017). The use of newly (or yet to be) developed echosounder and camera data processing algorithms should provide valuable information. Actual collisions between turbines and fishes are thought to be rare, but determining the effect of a collision on a fish will help understand actual impacts that can be used to model the population-level impacts of turbines.

Effects of underwater lights on fish behavior – The effects of lights used for monitoring fish behavior during periods of darkness should be examined to understand the potential influences of light on fish behavior and subsequent biases that may be introduced during nighttime monitoring of fish/turbine interactions (Matzner et al. 2017). Lights can either attract or repel fishes, and without knowing the exact effects of light on fish behavior on a species-specific basis, it is not possible to understand the sampling bias. Literature from research around hydroelectric dams may provide some insight.

Automated detection of fish collisions – Many monitoring methods still rely heavily on manual and visual processing. Although this approach likely leads to accurate results, it is time-consuming and, in some cases, prevents comprehensive monitoring (Matzner et al. 2017) or reporting. Efforts should be devoted to developing automated detection to better understand the frequency of the collision of fishes with turbines in the field and to avoid the need for manual processing of echosounder data. Further development of automated algorithms for both echosounder and camera data are also needed to reduce the burden of the storage and post-processing of collected data.

Correlation of fish behavior with stimuli – High-resolution information about fish behavior should be quantitatively correlated to stimulus fields around turbines, including noise, pressure, velocity, acceleration, and water particle characteristics, to advance understanding of fish behavior in response to these stimuli (Figure 3.6). Grippo et al. (2017) qualitatively examined these questions, but rigorous quantitative analyses are needed. To do this, fields around the operating/rotating turbine, including water velocity, pressure, acceleration, and water particle characteristics (Nedelec et al. 2016; Popper and Hawkins 2018) should be measured. Next, fine-scale fish behavior elucidated through tagging or other methods should be overlaid on the fields around the turbine, and correlations among environmental fields, physical covariates, and fish behavior should be determined. Conducting such an exercise would enable more accurate prediction of fish behavior in the absence of other means, such as field monitoring. In addition, there is a need to understand fish behavior in close proximity with turbines. In many cases, particularly when using echosounders to monitor fishes, the turbine blades and fishes are indistinguishable, or the turbine blades cause feedback and mask fish detections at close range (Shen et al. 2016).

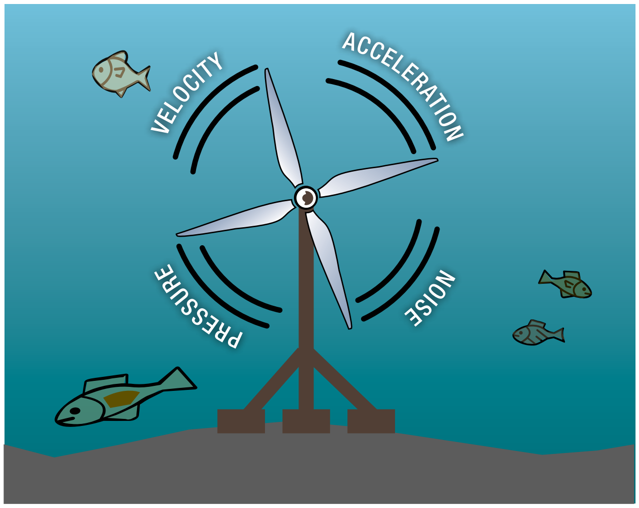


Figure 3.6. Schematic of stimulus fields produced by a turbine that could affect fish behavior. (Illustration by Robyn Ricks)

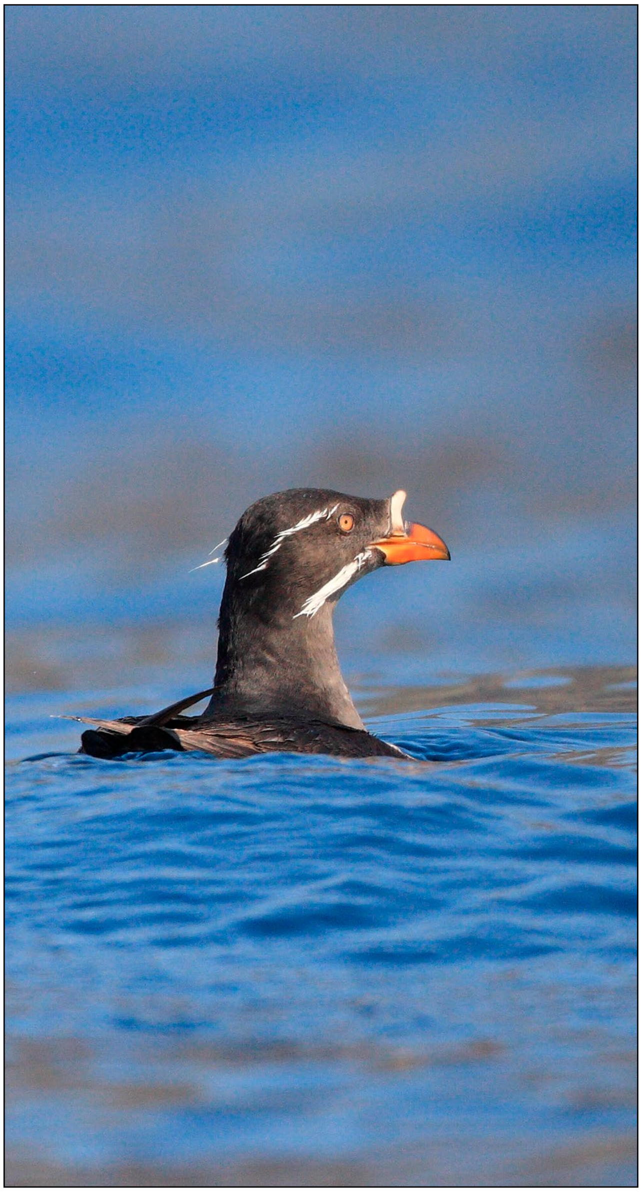
Consequences of the collision of fish with turbines – The outcomes of actual collisions of fishes and MREs are relatively unknown and should be examined. Even if a fish is not actually struck by a turbine, it may experience other sublethal behavioral and physiological effects. Investigating sublethal and non-contact effects will also be important for understanding the effects of turbines on fishes.

Optimizing turbine operation for fish safety – While also considering electricity production, research to identify optimum blade velocity should examine the trade-off between avoidance behavior and severity of injuries, because increased blade velocity results in increased avoidance behavior, while decreased blade velocity results in decreased severity of injuries and mortality (Zhang et al. 2017).

Realism and groundtruthing of collision and encounter models – Encounter probability models need to incorporate realistic representations of fish behavior, including avoidance and evasion behavior observed during field studies (Viehman and Zydlewski 2017). These models need to be rigorously groundtruthed to determine the realism of their outputs.

Effects of MRE arrays on fish – Future studies should examine the impacts of MRE arrays, which may have implications that differ substantially from those of single devices (Shen et al. 2016). The effects of turbines on fishes beyond the individual-turbine and individual-fish levels should be pursued as the MRE industry scales up. For example, how a device (or devices) affects the migration of groups of animals, such as schooling salmon or herring, over prolonged periods should be investigated, and expanded to include consideration of turbine arrays. It is likely that a turbine array will alter the biota in an ecosystem by repelling some species and attracting others (Fraser et al. 2018).

Implications of fish collision on populations – The population-level impacts of MRE devices on fishes should be determined using a variety of approaches, including using population dynamics modeling and examining long-term data about the abundance of fishes, to provide a more holistic understanding of fish collision risks. As the industry develops, regulators will have to consider the potential effects on fish populations, using data gathered from single devices and small arrays, and applying tools used in consideration of other development processes. Also of consideration are the community-level effects that might be caused by MRE development. By altering the fish community, ecosystem effects such as changes in the food web structure, as well as the overall and relative abundance of fishes, will likely be realized. Furthermore, an attractant effect, particularly of predatory fishes, may disproportionately affect other fish species, particularly low-abundance species like Atlantic salmon and some populations of Pacific salmon.



3.6.
COLLISION RISK TO SEABIRDS

Seabirds are considered to be at risk from tidal turbine development if they dive at the locations and depths of operational turbines. Understanding this risk involves understanding the geographic distribution, seasonal habitat use, diving depth and timing, and other behavioral movements of the seabirds of concern, as they may overlap with operational turbines.

3.6.1.
SUMMARY OF KNOWLEDGE THROUGH 2016

As of 2016, knowledge about the risk of seabird collision with MRE devices was limited, in part because of a lack of operational devices. Consequently, most studies focused on the potential vulnerability of seabirds' habitat relative to the presence of MRE devices rather than collision risk. While no empirical data were available about the collision impacts of seabirds with MRE devices, several studies assessed the relative sensitivities of different seabird species or species groups to the potential adverse effects of MRE devices (e.g., Furness et al. 2012; Wilson et al. 2007). Cormorants and auk species including European shag (*Phalacrocorax aristotelis*) and black guillemot (*Cepphus grylle*) were highlighted as the species most at risk because of their diving behavior and depth and the resulting potential for overlap with operating or moving turbine parts (Furness et al. 2012; Langton et al. 2011). Several studies used land- and boat-based visual observations to investigate seabird presence and use of tidal areas. Their findings suggested that although highly energetic tidal channels may provide predictable foraging sites for a range of seabird species, the specific details of habitat use and therefore risk will be site-specific and may also vary within a site (Wade 2015; Waggitt and Scott 2014).

Technology and remote observation methods were also used to investigate the potential impacts of MRE devices on seabirds. Williamson et al. (2017) used the Flow, Water Column and Benthic Ecology (FLOWBEC) platform equipped with a variety of sensors to assess the underwater interactions of seabirds (as well as fish and marine mammals) with tidal turbines. A similar integrated instrumentation system was also developed by Polagye et al. (2014). In addition, Jackson (2014) used above-water cameras on the Pelamis wave energy device at the European Marine Energy Centre (EMEC) in the Orkney Islands, Scotland, to assess the use of the wave structure and surrounding water by seabirds, and they found use by eight species, most frequently by Arctic terns (*Sterna paradisaea*). Floating tidal turbines operate near the surface; therefore, for these types of devices, the results from Jackson (2014) suggest the implications for collision risk should be investigated further. Bird-borne technology (particularly time-depth recorders) were also used to collect data about the potential risk from MRE devices, but it was not possible to couple the diving profiles of seabirds with GPS location data to gain dive profiles for seabirds at MRE sites. In the absence of empirical seabird collision data, collision risk models were under development to estimate likely collision rates (Grant et al. 2014; Scottish Natural Heritage 2016), but the data to parameterize the models were limited.

3.6.2.
KNOWLEDGE GENERATED SINCE 2016

Since the publication of the *2016 State of the Science* report, studies have continued to investigate habitat use and fine-scale interactions with turbines as well as the development of monitoring techniques, as a proxy for collision risk for seabirds and tidal turbines.

Site-wide Scale and Habitat Use

An understanding of seabird habitat use across a potential tidal-stream development site can provide information about the likelihood of a diving seabird and a tidal turbine co-occurring in two-dimensional space (i.e., latitude and longitude). Waggitt et al. (2016) used a combination of vessel-based seabird surveys, hydrodynamic modeling, and acoustic surveys to test for associations between diving seabirds and physical features in a tidal-stream environment—the Fall of Warness in the Orkney Islands, Scotland. Their results showed that for the species of interest (Atlantic puffins [*Fratercula arctica*], black guillemots, common guillemots [*Uria aalge*], and European shags), individuals were associated with fast and slow horizontal currents, high turbulence, upward and downward vertical currents, and hard-rough seabeds. However, the strength of the associations was species-specific. In particular, the study demonstrated a strong association of Atlantic puffins with fast horizontal flow, highlighting the potential for this species to be at risk of collision with tidal turbines. Following on from this, Waggitt et al. (2017) used data from shore-based seabird surveys across six sites in Scotland to identify trends in the use of habitats by black guillemots and European shags. However, their results did not provide any clear generalizations, suggesting that species habitat use of tidal-stream environments and the associated risk of collision with turbines may vary greatly between development sites.

GPS tracking of black guillemot breeding on the island of Stroma in the Pentland Firth, UK, found little overlap between birds and the MeyGen lease area; 73.2 percent of the GPS points fell outside the area (Johnston 2019). Foraging occurred at shallower depths (at mean depths of 24 m) and at slower tidal velocities than in the lease area. This may be due to the energetic cost of benthic diving in strong currents. The study found a large amount of individual variability in habitat use, suggesting that in addition to species- and site-specificity, individual specialization may modulate collision risk.

Cole et al. (2018) used a modified ornithodolite (a pair of binoculars with a built-in laser rangefinder, digital compass, and inclinometer) to quantify animal space use and the fine-scale space use in a highly dynamic tidal area (Ramsey Sound, Wales) by diving seabirds, to locate the birds. Their results showed that the standard deviation of distance measurements was 1–2 m within a 2 km range. However, systematic error in the laser rangefinder distance measurement, as well as the influence of the target bird size and color, could lead to an increase in the actual 3-D positional error (Cole et al. 2018). Despite these limitations, the ornithodolite is a useful tool for assigning individuals to locations in space and therefore for understanding how they might be at risk of collision. In relation to bird behavior and habitat use, they found that individuals avoided the main channel where mean current speeds were fastest, preferring instead the relatively slack waters. They also noted that diving birds oriented into the flow and could therefore potentially drift backward if their swim speed was less than the current speed, potentially drifting into a turbine if they occupied the same stretch of water (Cole et al. 2018). Similar behavior of "conveyor belt foraging" was documented by Robbins (2017) for black guillemots in Bluemull Sound, Scotland, where the density of black guillemots also showed a significant negative relationship with current speed.

Thirty-three bird species have been recorded in land-based surveys during the EnFAIT project in Bluemull Sound (Nova Innovation 2020). Fifteen species are known to dive to the turbine depth (≥ 15m below sea level), and therefore capable of encountering and interacting with the turbines. Black guillemot and European shag accounted for over 90% of all sightings, with other diving bird species, such as Atlantic puffin, northern gannet (*Morus bassanus*), common guillemot and red-throated diver (*Gavia stellata*) recorded infrequently. Black guillemot were recorded diving in the area immediately around the turbines in 2.75% of scans, European shag in 1.04% of scans and puffin in 1.08% of scans. For the 9 years of survey data, the modeled probability of a bird diving in the area immediately around the turbines is <0.05 for both black guillemot and Atlantic puffin, <0.03 for European shag and <0.01 for all other species. In general, the probability of birds diving around the turbines was greater on flood tides than the ebb and lower at faster tidal flows, indicating a very low turbine encounter risk for even the most commonly occurring diving birds. Black guillemot and European shag were the only bird species observed in the subsea video footage. Eleven occurrences of shag and seven of guillemot were observed, all during slack tide or periods of tidal flow below the cut-in speed, when the turbines were not operating. On three occasions, European shag were observed actively pursuing fish around turbines. No physical contact between birds and the turbine blades was ever observed in any of the footage.

Unmanned aerial vehicles (UAVs) have recently been used to understand how seabirds use tidal flow areas in high-flow tidal areas of the Pentland Firth (Williamson et al. 2018). Limited research has been conducted on the effect of UAVs on birds and specifically non-breeding, resting, or feeding birds (Vas et al. 2015) rather than breeding birds (Brisson-Curadeau et al. 2017; Weimerskirch et al. 2017). It is thought that the effect on behavior is minimal when UAVs are operated at appropriate heights, though this will be species-specific. UAVs provide a cost-effective method for measuring seabird distributions and hydrodynamic features concurrently. Vessel-based observers were used to confirm UAV observations of seabirds while their UAV hydrodynamic measurements were groundtruthed against vessel-based hydroacoustics (Williamson et al. 2018). This research aims to develop algorithms for the automated detection of animals and hydrodynamic features from UAV data. A UAV was used with vantage point surveys to observe top predators around a manmade structure (SeaGen) in Strangford Lough, Northern Ireland, demonstrating the presence of a predictable foraging hotspot for several tern species in the surface wake of the device (Lieber et al. 2019). During the study, SeaGen was being decommissioned and the rotors were removed, although the monopile was still in place, thereby creating a surface wake effect. It has been hypothesized that foraging hotspots generated around operational devices could potentially lead to an ecological trap, i.e., a situation in which birds are attracted to an operating turbine because of the increased foraging opportunities and consequently experiencing an increased collision risk (Lieber et al. 2019). An ecological trap occurs when "organisms make poor habitat choices based on cues that correlated formerly with habitat quality" (Schlaepfer et al. 2002). This behavior could increase the risk of collision, thereby outweighing the benefit gained from foraging (Battin 2004; Kristan 2003). The degree to which the surface wave effects observed at SeaGen might be replicated at depth by wakes created by fully submerged devices and any corresponding implications for the creation of feeding hotspots at depth is unclear.

Fine-scale Interactions

To better understand the risk of collision of seabirds with underwater turbines, it is vital to understand how individuals will interact with the devices. To date, there has been limited information about the underwater movements and behaviors of seabirds around tidal turbines, in part because of the low number of operational devices. A proxy for empirical data about interactions information has been collated about seabird diving behavior in an attempt to parameterize collision risk models. Robbins (2017) produced a synthesis of data about seabird diving behavior (18 different parameters) for 22 species found in UK waters. This study found that existing knowledge of foraging and diving behavior is highly variable across species and parameters and that for some of the most vulnerable species, such as loons and black guillemots (Furness et al. 2012), data uncertainty is high. For such species, targeted research will be required.

Guidance on Collision Risk and Monitoring

Since the publication of the *2016 State of the Science* report, Scottish Natural Heritage has published guidance on how to assess collision risk between underwater turbines and marine wildlife, including diving seabirds (Scottish Natural Heritage 2016). The guidance presents three separate models: (1) the Encounter Rate Model, (2) the Collision Risk Model, and (3) the Exposure Time Population Model. The approaches of the Encounter Rate and Collision Risk Models are similar to those used for wind turbines (Band 2012); they use a model for the turbine and the animal to estimate the likely risk of collision. The Exposure Time Population Model takes a different approach; it uses population modeling to determine "the critical additional mortality due to underwater collisions with a turbine which would cause an adverse effect to an animal population" (Scottish Natural Heritage 2016). All three models require data to parameterize, and recommended values for some of these standard parameters, such as biometrics (body length and wingspan) and diving behavior (dive depths, swim speeds, etc.), are provided in the guidance. The guidance can be used to determine which model is best suited to the specific circumstance of an MRE development and for the data available.

3.6.3.
RESEARCH AND MONITORING NEEDS TO RETIRE THE ISSUE

Significant data gaps remain because only a limited number of studies have been conducted, so there is no evidence to show that direct interactions with tidal turbines will occur or cause harm to individual seabirds or populations.

Seabird Movement and Behavior – There is a lack of data about and observations of nearfield animal movements and behaviors around tidal turbines, which would be required for a variety of designs and across a range of tidal locations. This means that we do not currently understand how seabirds interact with operational turbines and we are unable to predict how devices might affect individuals at new development sites, which limits the evidence base for environmental impact assessments. This is also evident when using collision risk models, which currently make assumptions about avoidance or evasion responses of seabirds, based on learning from offshore wind turbines (Scottish Natural Heritage 2016), because there are no empirical data from tidal turbines.

Detecting Collisions – Even if more data about the close-range behavior of seabirds relative to turbines become available, it will still be necessary to detect and record actual collision events, and doing so may not be possible because of poor underwater visibility and turbidity (RPS Group 2010). Having empirical evidence of collisions (or the lack thereof) not only allows for a better understanding of risk but will aid in the validation of collision risk models. In addition, there is a lack of information about the consequences of collisions for seabirds, if they occur; i.e., whether a collision event would lead to mortality. Research has started to address this issue for marine mammals but it has yet to be explored for seabirds (Onoufriou et al. 2019).

Seabird Species Behavior – Gaps in our knowledge of seabird diving behavior remain. Although some seabirds are well-studied, studies often focus on a limited number of species at only a few locations. The synthesis of marine bird diving behavior conducted by Robbins (2017) to inform our understanding of the risk of underwater collision with tidal-stream turbines found that data gaps remain, particularly for some vulnerable species such as black guillemots and loons. Data need to be collected from more than one location over several seasons including the breeding season. Improved data should be used to parameterize underwater collision risk models.

Seabird Use of Tidal Races – Wade et al. (2016) incorporated uncertainty into an assessment of seabird vulnerability relative to MRE developments and found high levels of uncertainty associated with seabird use of tidal races. This affects confidence in our estimates of the likely risk of collisions between diving seabirds and tidal turbines, so wherever possible uncertainty should be presented transparently. However, careful consideration should be given to who is communicating the uncertainty, in what form, and to whom, as well as importantly, for what reason (van der Bles et al. 2019).

Research Priorities – Many of the priorities for reducing the risk of seabird collisions with tidal turbines overlap with those proposed for marine mammals and fish, and many remain from those recommended in the *2016 State of the Science* report. The priorities that could be addressed by research, monitoring, and methods and tools, are listed below.

Priorities for research include the following:

- Improve the knowledge of seabird diving behavior where knowledge gaps remain for vulnerable species to increase the evidence base for use in estimation of collision rates in models.
- Develop collision risk methods that incorporate the movement of seabirds around turbine arrays rather than around single turbines.
- Test the assumption of collision risk models that all mortality is associated with collision events.
- Include variability and uncertainty in collision risk modeling.
- Improve the understanding of the displacement of seabirds from operating tidal energy sites to understand the true size of the population at risk.

The priorities for monitoring at future tidal energy development sites are as follows:

- Monitor nearfield underwater interactions with and behaviors of seabirds in response to deployed devices.
- Target observations (rather than generic monitoring) of seabird habitat use in relation to hydrodynamic features to improve the understanding of how seabirds use high-flow environments.
- Target observations to determine the extent of displacement effects.

The priorities for the development of technology, methodologies, and tools include the following:

- Develop methods to improve the understanding of the behavior of seabirds around operating devices, particularly avoidance and evasion behaviors.
- Develop sensors and cameras to assure that any collisions can be detected with confidence and that collisions can be classified by species, and to determine the effects/consequences of collision (i.e., mortality rate).
- Develop automated methods for processing the large quantities of data, such as underwater video/camera images, that are often recorded at sites.

3.7.
CONCLUSIONS AND RECOMMENDATIONS

Key progress has been made to better understand collision risk, and evidence is steadily growing across a range of disciplines, informed by research and post-installation monitoring of operational devices. No collisions have been observed in nearfield monitoring carried out to date around operational turbines. However, because deployments have been limited and monitoring challenges are significant, gaps in knowledge remain. It is also important to acknowledge that the absence of observations of collisions does not provide definitive evidence that collisions will not occur. Uncertainty about collision risk, including the potential for collision events to occur, continues to be a significant influential factor in consenting processes and their outcomes for tidal and river energy developments. The increase in turbine device and array deployments, coupled with increased reporting about the findings derived from monitoring at existing operational projects over the next few years, will be critical in addressing some of the key gaps and uncertainties. Crucial to this effort will be improving the dissemination, sharing, and use of the data gathered around operational devices, and the information generated from these data, in a way that does not compromise any commercial confidentiality or intellectual property for device developers, suppliers, or researchers.

3.7.1.
INTEGRATION OF INFORMATION, TECHNOLOGY, AND ENGINEERING EXPERTS IN MONITORING PROGRAMS

Improvements in the methodologies used to collect, store, share, and analyze data pertaining to collision risk are required. Key to achieving these improvements will be better integration, from the design stage, of the efforts of experts in engineering and information technology to improve the technologies used in monitoring (including improved reliability, survivability, and cost), as well as managing, analyzing, and disseminating the data. The development of automated data processing algorithms and software for analyzing data gathered around operational devices will be key to resolving uncertainties about collision risk.

In addition, it is vital to examine the overlap and potential interaction that may occur among predator and prey species, through the integration of data collected about marine mammals, fish, and diving seabirds around turbines (Scott et al. 2014). By collecting data about the three major groups of marine animals at risk through coordinated monitoring programs (adding sea turtles in appropriate waters), the understanding of the potential interactions around MRE devices will be improved for each group and the potential interactions between the groups, such as the availability of forage fish around turbines forming prey for marine mammals or seabirds, will be better elucidated.

3.7.2.
EVIDENCE OF FACTORS AFFECTING COLLISION RISK

The broad-scale use of tidal energy areas by mobile marine predators for feeding and foraging is well-established (e.g., Benjamins et al. 2015). However, recent research presented in this chapter indicates that collision risk is more nuanced than the straightforward spatial overlap of animals with tidal and river energy areas. Predator occupancy patterns appear to be strongly associated with tidal phases, current strengths, and flow structures, most likely in response to forced prey distribution and behaviors (Lieber et al. 2018, 2019), which will affect the likelihood of spatial overlap at times of risk (i.e., when turbine blades are rotating). There appears to be some heterogeneity in these associations across different tidal sites (e.g., Waggitt et al. 2017) but also some differences (e.g., Hastie et al. 2016). As evidence of the influence of fine-scale hydrodynamics on marine animal distribution and behavior in tidal energy habitats grows, it will improve our understanding of the probability of encounters with operating tidal devices, and the corresponding implications for collision risk.

Where there is spatial overlap between operating tidal devices and marine animals, the animals' behavioral responses to the physical and acoustic presence of devices will be the primary factors influencing collision risk. Such responses include attraction, avoidance, and evasion. These factors can be better understood by measuring the response of marine animals to the actual presence of installed devices and arrays.

3.7.3.
ASSESSING COLLISION RISK AND ITS CONSEQUENCES

Assessments of collision risk for tidal energy projects often include the use of predictive models to quantify potential collisions (e.g., Scottish Natural Heritage 2016) and the likely consequences of such predictions for species' populations (e.g., King et al. 2015). In general, collision models are relatively simple, based on the broad spatial overlap of marine animals with tidal energy development areas, and on the measured or estimated animal density, often across a much wider area. Outputs should therefore be treated with caution to avoid inflating their scientific basis. Outputs provide a useful indication of the potential magnitude of collision risk, but contextualization and interpretation also are crucial.

Equally uncertain are the consequences to an individual animal if a collision with a moving part of a turbine were to occur. For some species, the research is moving beyond the assumption that all collisions will result in the death of the animal, but the potential consequences for marine mammals across the size range from small pinnipeds and cetaceans to large whales, as well as fish and diving seabirds, are not well known. More investigations are needed to assure that an overly conservative approach to predicting the outcomes of collisions can be avoided.

A key driver of the global concern about collision risk is the potential for such effects to lead to losses of individuals, which may affect ecosystem dynamics and the long-term status of populations. For many species, particularly those with spatially restricted, declining, or small populations, even a very low collision risk could result in concern about its effects on long-term population viability. For many species, limited evidence of life history or population demographics presents a challenge to understanding the potential for such effects. In the case of some species of "charismatic megafauna," the loss of individual animals might be deemed unacceptable from a societal or legal, rather than biological, perspective.

3.7.4.
POST-INSTALLATION MONITORING OF COLLISION RISK

Globally, uncertainty and knowledge gaps about collision risk have been key drivers of the requirement for and design of post-installation monitoring programs for tidal and river energy projects (see Chapter 12, Adaptive Management with Respect to Marine Renewable Energy). This is an area in which there has been significant activity in recent years, and there is a growing body of evidence about the interactions between animals and tidal devices. Significant progress has also been made in the development of monitoring techniques and instruments to address the challenges of gathering robust information of relevance to collision risk in tidal energy environments and around operating devices (see Chapter 10, Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines).

The increase in tidal device and array deployments, as well as reporting on the findings of existing operational projects over the next few years, are expected to further address some of the collision risk critical gaps and uncertainties. These efforts include opportunities for meta-analyses across multiple sites and projects. Key to the success of this work will be the MRE industry, regulators, researchers, and funding agencies working collaboratively to understand how to best fund, share, and disseminate the results of research and monitoring programs to collectively move toward a better understanding of collision risk. This will require the exploration and development of mechanisms for sharing data and information without compromising commercial interests or intellectual property rights, as well as consideration of the needs of the consenting processes, including independent review and scrutiny of outputs.

3.8.
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NOTES

Collision Risk for Animals Around Turbines

Sparling, C.E., A.C. Seitz, E. Masden, and K. Smith. 2020. Collision Risk for Animals around Turbines. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 28-65). doi:10.2172/1632881

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

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