A Review of Methods and Models for Environmental Monitoring of Marine Renewable Energy

Anke Bender*[1], Francisco G. A. Francisco*, Jan Sundberg*

*Department of Engineering Science, Division for Electricity, Uppsala University
Box 534, SE-75121 Uppsala, Sweden

[1]anke.bender@angstrom.uu.se

***Abstract*— A continued expansion of the marine renewable energy sector will result in an increased demand in monitoring the natural marine environment. This may be due to a basic scientific interest but is foremost linked to the requirement of pre- and post-construction studies in relation to environmental impact assessments and consenting processes for marine renewable energy projects. With focus on wave and tidal power, but without attempting to provide a comprehensive list, we review methods, technologies and other scientific tools used for monitoring and predicting possible impacts from marine energy installations, on both population and behavioural levels. This includes traditional methods such as fishing gear, like nets and cages, modern technologies such as platforms with multi parameter equipment and the use of deterministic models. This paper is intended to serve as an overview for technology developers as well as authorities, regulators and decision makers with interests in general techniques, and naturally for scientists and consultants commonly being executors of studies and monitoring programs. By giving relevant and up to date references this paper may also be useful for finding more detailed information on study methods and variants. Finally, we give recommendations on where development of technologies is needed in order to face future requirements.**

***Keywords*— Environmental monitoring, Monitoring techniques and platforms, Models, Impact assessment, Wave power, Tidal power, Offshore windpower, Marine renewable energy**

I. INTRODUCTION

The world energy demand is continuously increasing due to new industries, growing human population and transition from fossil fuel to renewable energy. The expansion of the marine renewable energy sector, aiming to deliver clean and sustainable sources, leads to an increasing demand in environmental monitoring. Marine habitats are already under severe pressure from other human activities such as fishing, boat traffic, mining and others [1]. Tidal and wave power are rising technologies which are on the way of becoming established energy resources such as offshore wind power. However, technical and non-technical barriers still need to be overcome for a full commercial use of marine renewable energy (MRE). One of the barriers is the uncertainty of possible environmental impacts of these new technologies. There is a need for adequate research to underpin decisions on site selection and the design of future projects to maximise potential ecosystem benefits and minimise potential ecosystem degradations [2] and [3].

Environmental monitoring procedures should be a naturally accepted part of all renewable energy projects and consenting procedures, and in most cases they are. One important issue is to detect possible impacts early and thus provide the chance for mitigation during all phases from pre to post installation.

With the complex spatial and temporal aspect in mind it is even more important to have a common reliable basis of monitoring methods, procedures and standardisations. Methodology determination is depending on various factors such as present stressors, the used technology and the MRE device characteristics, as well as the receptors such as keystone species, organism groups or habitats. Not at least, economical capacities of the project influence the choice of monitoring methods. In the case of tidal power installations, moving parts are of special attention for marine mammals, birds and other migrating species but also wave power devices can contain threats for species or habitats [2]–[4]. The receptor such as species of concern or red listed species, populations or habitats are often the key aspect when it comes to site selection. The complexity of selecting suitable methods becomes clear when merging aspects of different stressors, receptors and the variety of modern and traditional monitoring methods including models. Additional to the temporal scale, the phase of the project affects the choice of monitoring methods. The construction phases can be distinguished between pre- to post-construction phase in which each phase displays different characteristic disturbances.

With focus on wave and tidal power, but without attempting to provide a comprehensive list, we review methods, technologies and other scientific tools used for monitoring and predicting possible impacts from marine energy installations, on both population and behavioural levels.

II. TRADITIONAL MONITORING METHODS

Traditional monitoring methods of marine fauna can be divided into active and passive applied gear, grab and core samplers and survey methods by boat, plane or diving. Actively towed nets such as trawl or dredges are assigned to active capture techniques and often have destructive impact to the habitat or species. See also Table III for further listings of methods. Passive capture techniques such as fyke nets, gill nets or cage fishing gear are dependent on the movement of the animals itself. Many classical monitoring methods emerged from commercially used fishing methods. The following section presents commonly used traditional methods

ISSN 2309-1983

for environmental monitoring. Application for monitoring of the physical environment are partly common as well, but are here not further mentioned. The cited references provide additional illustrations and schemes of the respective tools.

A. Core and grab samplers

Core and grab samplers are benthic sampling devices of different sizes and mechanisms with the application in biology and geology. Beside application for sediment analyses and geological matters, essential target species resemble benthic invertebrate species.

Whilst various types of grab and core samplers for seabed substrata and benthic infauna exist, the choice of sampling devices is mainly determined by the hardness and compactness of the sediment. Many benthic sampling devices are unsuitable for coarse sediments such as the Day grab or the Van Veen grab samplers [5]. Coarse sediments will hinder the penetration of the sampling device and prevent proper sealing of the core barrel or grab sampler [6]. However, both the Day grab sampler (standard sampler for most UK infauna sampling) and the Van Veen grab sampler (mainly used in continental Europe) are widely used due to their easy deployment. Samplers like the Vibrocorer are appropriate for sampling in coarse sediments. The method is widely used in geoscience and the deployment requires large boats and winches due to the weight of the corer. Generally, grab samples allow quantitative and qualitative evaluation of the benthic infauna community and are possible to apply during all phases from pre- to post- deployment. The sampled surface area for the small Van Veen grab sampler and Day grab sampler is about 0,1m^2, and smaller for the Vibrocorer with about 0,01m^2 – 0,007m^2 [7] and [8]. This small surface area makes it unsuitable for macro faunal investigations [6]. One drawback is that larger benthic epifaunal species and motile species with fast avoidance reaction might not be covered by these methods [5]. For this purpose, other sampling techniques, such as semi-qualitative towed devices for example dredges or trawls but also cage fishing are more applicable. In this regards, alternative techniques for in-situ surveys might be high definition video and photography, diving surveys or an appropriate active or passive acoustic method. It is important to choose a suitable combination of methodologies in order to obtain a meaningful synthesis of the different biota and animal populations.

Key parameters
-Infauna community and benthos
-Quantitative and qualitative data
-Special equipment and personnel might be needed depending on the dimension of the sampler
-Applicable during all phases, pre- to post-deployment

TABLE I
OVERVIEW OF TRADITIONAL CORE AND GARB SAMPLERS, MODIFIED AFTER [5]

Sampling device	Sampled surface area	Weight of gear without sample	Suitable for coarse sediment
Mini-Hamon Graber	0,1m^2	300kg + additional weight up to 300kg	Yes
Day Graber	0,1m^2	80kg + additional weight up to 80kg	No
Van Veen Graber	0,1m^2- 0 ,2m^2	80-100kg	No
Costerus Graber	2x0,1m^2	400-480kg	Yes
Shipek Graber	0,4m^2	80kg	Yes
Hapscore Graber	0,015m^2	108-168kg	Yes
Vibrocorer	0,007-0,01m^2	1450-3500kg	Yes

B. Actively towed nets - trawls and dredges

These nets are designed to be actively towed over the seabed. Trawls and dredges exist in various types. These devices are made to sample epifaunal assemblages and can be used almost over any type of seabed even over rocks. Epifaunal organisms such as fish, crustacean and other invertebrate species have a wider size-range compared to the infauna community. They are better covered with actively towed trawls or dredges, compared to core and grab sampling devices. Trawl and dredges are designed to sample over the seabed. However, trawling devices also exist in pelagic variants, such as midwater trawls, in order to target pelagic species. Similar to the core and grab samplers, the use is also dependent on the type of seabed. It is to notice that samples can be partly destroyed by stones when the net is applied on boulder areas.

Assessing semi-quantitative estimates of population densities for comparative purposes requires the standardization of conditions and duration of towing. It is necessary to record start and end positions to calculate appropriate towed distances. However, this is not easy, especially in deeper waters. To facilitate this process, various tools such as towed cameras, measuring wheels, trawls with a mechanically activated device for opening and closing the sampler or real-time video systems are applied [9].

Local variations and heterogeneity of seabed conditions can limit the towing speed. A general guideline implies an even towing speed, with a maximum of 1,5kn [5]. Dredges should be avoided when trawls are possible to be used, due to their damages on the seabed.

Actively towed nets can be useful during pre- and post-construction phases of wave and tidal power devices. Spatial problems caused by deployed devices favor the use of other monitoring methods.

Key parameters
-Epibenthos (fish, crustacean and other invertebrate species)
-Semi-quantitative or qualitative data
-Special equipment and personnel might be needed depending on the dimension of the gear
-Possible spatial problems caused by deployed devices

C. Passive capture techniques for fish and macro crustacean (nets, cages and traps)

Passive techniques involve capturing the animal by their behaviour and movement [10]. Passive devices are generally simple in design and use. Typically there is no need for specialized personnel neither large vessels [10], but involvement and support of experienced fisherman can be useful. Samples from passive nets and cages are taken continuously over a period of time e.g. 12h / 24h, which has the advantage of dampening the effect of diurnal variations in fish or macro crustacean behaviour [11]. However, all passive sampling devices have certain selectivity for sizes, species or gender of animals that must be considered for data analyses. The following section presents three different methods: 1. Gill nets, 2. Cages, creels, pots and 3. Fyke nets. For each method, there are various sub techniques that can be used for monitoring purposes (see Table II).

1) Gill nets: Gill nets are commonly used in commercial fishing in both fresh and saltwater, and are a common tool for sampling of fish communities for monitoring purposes [12]. The plane net panel can be up to 100 m long and gill nets exists for both benthic and pelagic conditions. Gill nets are known to have a high degree of size selectivity towards underestimation of small individuals [12].

From an ethical point of view an obvious drawback of this method, as with other methods such as trawling or dredging, is animal mortality. For long-term observations involving capture and recapture of individuals, this is undesirable and other methods such as cages or fyke nets should be applied.

Key parameters
-Demersal and benthic fish and macro crustacean
-Qualitative data
-No special equipment or personnel necessary
-Possible spatial problems caused by deployed devices

2) Cages, creels and pots: The use of cages for experimental studies has a long history and can be useful for monitoring purposes and experimental field studies around renewable energy installations. Capture recapture, telemetry and other marking techniques are complementary approaches in monitoring practices and require vital individuals with good health conditions. Fishing cages and fyke nets provide such techniques [13].

The enclosure of individuals into cages was used by [14] to detect behavioral abnormalities of rock crabs, exposed to electromagnetic fields from subsea cables. Nedwell et al. 2003 [15] used cages to investigate potential behavioral changes of caged brown trout while exposed to noise from pile driving during the installation of renewable energy devices.

Using fishing cages for assessing the community of fish or macro crustacean species is a method applicable in different scales. Cages are easy to handle and implementable on any kind of seabed [10]. Furthermore, as a non-destructive method neither for the habitat nor the caught species, it is suitable to combine with tagging techniques as well as capture and recapture experiments to investigate population dynamics. Size and type of cages can limit the diversity in sizes and species of the capture. Most cages are designed for commercial fishing and are therefore selective for rather large sized individuals. This makes it difficult to cover a veritable reflectance of the community composition. Still, commercial species are often of especial interest in impact assessments.

Key parameters
-Demersal and benthic fish and macro crustacean
-Qualitative data
-No special equipment or personnel necessary
-Applicable during all phases; pre- to post-deployment

3) Fyke nets: Fyke nets are a type of passive sampling devices which rely on the willingness of fish and crustacean to enter the net; therefore, biased towards more active species [10]. Bait is often used to attract individuals and obtain high catch rates. It is common to use alongside cages, but it may influence species composition of a catch towards predator dominated species [11].

Fyke nets mainly target demersal and benthic fish species as well as macro crustaceans [11]. This method is usually applied in costal zones, freshwater or general shallow waters [10]. Applications are suitable for complex habitats with for example vegetation. Unlike gill nets or actively towed gears for fishing such as trawl, individuals can be released after being captured. In this respect it is comparable with the use of cages. With the help of leaders and wings, fyke nets cover larger areas compared to cages. Applying fyke nets in strong currents or deep water can be problematic and predation inside the net can also occur and must be considered [11].

Key parameters
-Demersal and benthic fish and macro crustacean
-Qualitative data
-No special equipment or personnel necessary
-Applicable during all phases; pre- to post-deployment

TABLE II
OVERVIEW OF TRADITIONAL PASSIVE SAMPLING DEVICES SUBDIVIDED FOR DIFFERENT DEPTH RANGES, MODIFIED AFTER [10]

Bottom (benthic)	Midwater (pelagic)	Near shore
Gillnet; sinking	Gillnet; suspended	Gillnet; sinking
Trammel net; sinking	Gillnet; drifted	Trammel net; sinking
Pot/Cage gear	Trammel net; drifted	Fyke net
Angling gear; sinking	Angling gear; suspended	Trap gear
		Pot/cage gear
		Angling gear; sinking

D. Survey methods

Visual surveys conducted from boats or planes to monitor birds, marine mammals and turtles for monitoring purposes can also be suitable for the collection around renewable energy sites [16]–[18]. A combination of aerial survey and the use of high resolution digital photo or video material to estimate and determine individuals can be useful [19]. The right timing and experienced personnel are key aspects when it comes to visual sightings.

When focusing on birds, marine mammals, turtles and sharks, active acoustic and passive acoustic methods and the use of radar and telemetry tagging can be complementary and indispensable methods [20] and [21].

Scientific SCUBA Diving is assigned as traditional multi-purpose survey technique. Diving is a non-destructive visual survey technique, providing an image of species composition at locations even very close to renewable energy devices, where other monitoring methods such as nets or cages cannot reach [22]. It also covers small and cryptic species which cannot be observed by active or passive acoustic instruments [23] and [22]. However, the presence of divers can scare species and rapidly moving animals can hinder exact recordings of numbers of individuals and species [9]. Additionally, diving can support taking quantitative samples such as sediment cores [24], [25], suction samples [9], applying cameras [24], sampling along transects [25], [26] or can conduct experimental studies. Still, as handy the method of diving might be, there are limitations and the use of it as an initial survey method is unsuitable. Restriction to certain maximum depths, limitation in exposure time, life risks, high costs and the need of calm weather and visibility conditions cannot always be meet and fulfilled at MRE harvesting sites.

Key parameters

-Survey method is selected depending on target species
-Qualitative and semi-quantitative data
-Special equipment and skilled personnel necessary (camera, boat, plane, diving equipment)
-Applicable during all phases; pre- to post-deployment

III. UNMANNED MONITORING TOOLS

In MRE projects, environmental concerns are often related to potential collision risks between marine animals and underwater structures, potential occurrence of reef effect, amongst others. Apart from high operational costs, traditional monitoring techniques, e.g. visual observations or biological sampling, are greatly limited by weather conditions, safety issues and survivability in high-energetic sea conditions [27] and [28]. Therefore the use of other methods such unmanned platforms, have been increasing over the years. Unmanned environmental monitoring platforms can be either fixed or moving vessels. The class of moving platforms can be remotely operated vehicles (ROV) or fully autonomous vehicles (AUV) that operate on the surface or can be submersible. The vehicles can be used for a variety of missions and can take several monitoring instruments on-board. Some examples of moving platforms are, Autonomous Underwater Vehicles (AUVs), underwater buoys and gliders, remote operated vehicles (ROV), drifting buoys, towed underwater vehicles, satellites, airplanes [29] and [30]. Drones could emerge as a new monitoring tool and seem to have a promising future in the field.

Fixed platforms can be fitted with echo sounders, sonar systems, acoustic water column profilers, hydrophones, C&T-PODs, cameras among other instruments (see Table III). Table III lists commonly used and well known instruments, however, others exist. For biomass estimation and fish behaviour, the use of surface buoys or fixed structures located at target points is the most common approach [31]–[34]. Fixed platforms are also, if not mostly, used to house resource assessment instruments that measure physical variables such as wave, wind and currents. Fixed platforms are commonly (commercially) named as data buoys. They can be found in several sizes and types, as an example are the buoys of the National Data Buoy Center (NDBC) [35]. More information about the development of data buoys can be found in [36]. Fixed platforms also integrate sensors for physical (temperature, salinity, turbidity, pressure, tide), optical and chemical observations (dissolved oxygen, chlorophyll-a, nitrate, oil spill) [37]. When the interest is to observe sea bird behaviour in MRE farms, X-band marine RADAR (radio detection and ranging) can be used [38]–[41].

ROVs provide the possibilities to accomplish most of the tasks that divers can perform at lower risk and cost. Moreover, the use of techniques for quantitative sampling that could only be done by a direct human supervision can now easily be done by ROVs. An example is the development of ROVs that can monitor and control the invasive population of lionfish in the Atlantic Ocean by capturing individuals in a certain quota per dive [42].

Unmanned monitoring platforms such as submersible equipped with cameras, sonars and sediment traps can be used to perform extensive monitoring of biomass that could only be done by divers at limited time and space resolution.

TABLE III

OVERVIEW OF MONITORING INSTRUMENTS PARTIONED FOR DIFFERENT FUNCTIONS AND APPLICATIONS

	Instruments	*Applications*	*Functions*
Active Acoustic	ABS	⑬⑭	Measurement of particle size within the water column
	ADCP	①⑫⑮	Water column profiler of current velocity, plankton
	Altimeter	①⑨⑪⑯	Depth estimation
	AWCP	②③⑬	Water column profiler of plankton, nekton & fish
	Echo sounder	②③④⑧⑫⑭	Tracking of fish, plankton, marine mammals, marine organisms, aquatic vegetation, gas bubbles, oil droplets, depth, substrate classification, water masse
	Imaging sonar	③④⑧⑨⑩⑰⑱	Acoustic images of underwater objects, and bottom features, fish, marine mammals
	Multibeam sonar	①②③④⑤⑧⑨⑪⑫⑯⑰⑱	Bottom topography, leak detection, tracking of fish, marine organisms & mammals, underwater object detection
	Scour monitor	⑪⑬⑭	Detection & monitoring of erosion near foundations
	Sonar	②③④⑤⑦⑧⑨⑩⑪⑫⑬⑭	Tracking of marine organisms, fish, marine mammals, underwater objects
	Subbottom profiler	①⑨⑮	Identification & characterization of layers of sediment or rock under the seafloor
	Acoustic anemometers	①⑫⑮	Measurement of wind velocity
Passive Acoustic	Hydrophone	④⑦⑧	Tracking of underwater sounds of manmade objects, marine organisms & mammals, background noise, anthropogenic noise incl. leak noise.
	C&T-POD	④⑦⑧	Tracking sound emitted by marine mammal
Electromagnetic	RADAR	①⑧⑮	Monitoring of surface currents & waves, birds, marine mammals.
	Tidal gauge RADAR	①	Measurement of tidal heights
	CTD	⑬	Salinity (conductivity), temperature, depth (pressure), dissolved oxygen, chlorophyll.
	Electromagnetic current meter	①	Measurements of current velocity
	EMS - meter	③④	Measurement of electromagnetic field
Optical	Camera and video	①②③④⑤⑥⑦⑧⑨⑩⑪⑮ ⑰⑱	Marine organisms, fish, corals, marine mammals. Structural inspection, gas bubbles, leak detection, navigation etc.
	Fluorometer	⑬⑰	Chlorophyll A, fluorescence, oils spill monitoring
	Laser Doppler anemometry	①	Measurement of wind velocity
	Turbidity meter	⑬⑭	Measurement of particle size within the water column
	Secchi disk	⑬	Water transparency
	Radiometer	⑬⑰	Monitoring of diffuse attenuation, photosynthesis, energy flux, & several other optical water properties.
	Infrared Camera	③④⑤⑦⑧⑨⑩⑪⑫⑱	Structural inspection, gas bubbles, leak detection, navigation. Monitoring of marine organisms, fish, and corals.
	LIDAR	③④⑨⑭⑯	Mapping and characterisation of the seabed and monitoring of fish and marine mammals
Electro-mechanic & Manual	Current meter	①	Measurements of current velocity
	Wave buoy	①⑮	Sea state estimation, wave measurements
	Flow meter	①	Measurements of volume of water passing through a controlled sector
	Sediment sampler	①⑤⑨	Various samplers for different forms of sediment samples
	Dredge and Trawl	①⑤⑨	Benthos and Epibenthos collector
	Water sampling bottle	⑬⑰	Bio-chemical water properties (plankton, nutrients, etc.)
	Net	②⑬	Fish, plankton, suspended marine organisms
	Cage	②⑤⑦	Fish, crustaceans, other marine organisms
	Diver	⑤⑥⑦⑨⑩⑬	Sediment collector, inspection, biomass estimation, etc.
	Submersible	③④⑤⑥⑦⑩	Sediment collector, inspection, biomass estimation, etc.
Platforms	Moored buoy	①②③④⑤⑦⑫⑬⑮⑰⑱	Multi-parameter monitoring
	AUV	①②③④⑤⑥⑦⑨⑨⑪⑫⑮ ⑯⑱	Multi-parameter monitoring
	ROV	⑤⑥⑦⑨⑩⑪⑬⑰⑱	Multi-parameter monitoring, inspection, navigation
	ROSV	①②③④⑤⑨⑩⑪⑫⑬⑯⑰ ⑱	Multi-parameter monitoring, inspection

Explanations

Resource assessment & monitoring ①
Biomass estimation ②
Fish behaviour ③
Marine mammal behaviour ④
Benthic monitoring ⑤
Biofouling ⑥
Reef effect ⑦
Collision risk monitoring ⑧
Seabed inspection ⑨
Structural inspection & monitoring ⑩
Erosion monitoring ⑪
Wake & turbulence monitoring ⑫
Water quality monitoring ⑬
Sediment transport monitoring ⑭
Sea states & weather monitoring ⑮
Bathymetry ⑯
Oil spill & other leaks ⑰
Navigation & positioning ⑱

ABS: acoustic backscatter sensor
ADCP: acoustic Doppler current profiler
AUV: autonomous underwater vehicle
AWCP: acoustic water column profiler
CTD: conductivity temperature depth
LIDAR: Light detection and ranging
ROV: remote operated vehicle
ROSV remote operated surface vehicle
T/C-POD: porpoise detectors

Today, most of the deep sea fish nets are deployed and supervised with the aid of towed under water vehicles equipped with multibeam and imaging sonar systems, cameras and thrusters that can steer the net to precise location where a school of fish is located. Although, practically any instrument can be on board of such platforms, it is more common to have acoustic instruments for biomass monitoring, water property measurements, and seabed inspections.

There are several platforms already developed specifically for monitoring MRE devices. The FORCE project in the Bay of Fundy integrated acoustic instruments such as multibeam, side scan sonar systems, and hydrophones, among other water column and seabed profilers in order to monitor the space surrounding tidal power turbines [43]. The European Marine Energy Centre LTD (EMEC) has developed its own monitoring platform which integrates several measurement instruments such as a current profiler, hydrophones, a sonar and a Conductivity, Temperature and Depth sensor (CTD). The NERC/Defra collaboration FLOw, Water column and Benthic Ecology 4-D (FLOWBEC-4D), is basically a set of sonar systems designed to monitor marine animals within a designated water column. Uppsala University has been developing an underwater multipurpose platform that can host dual-beam, split-beam and multibeam sonar systems, acoustic Doppler profilers (ADCPs), cameras, hydrophones sediment traps among other devices [31].

As above mentioned, an unmanned monitoring platform can house virtually any kind of instruments or sensor for environmental monitoring of MRE devices, and Table III covers examples of a large number of instruments that could be integrated onto platforms.

Due to its versatility, safety, low-logistics, and cost-effectiveness, unmanned monitoring platforms can be seen as advanced tools that complement the traditional and more stablished methods.

Fig. 1 Top side of the submerged tripod platform unit, equipped with a multibeam sonar, splitbeam sonar and a video camera [44].

IV. Models

The use of mathematical and numerical models in biology dates back to the end of the 18th century when T.R. Malthus and P.F. Verhulst developed models explaining the basics for population growth rates first implemented in fisheries for understanding of possible fish stock yields. In the 1920s, when ecology as a science yet was in its cradle, and inspired by theories of economics, A. J. Lotka and V. Volterra developed the first deterministic population dynamic model which became a cornerstone in understanding animal population dynamics. Over the years models have been further developed and inspired several fields of ecology, from basic research to more applied conservation ecology.

Basically, population size depends on number of births and deaths but also migration. All population do vary in number over time due to natural causes, depending on factors such as climate variability (including catastrophic events), variation in food resources etc. Expanded and more in detail factors such as individual fitness (relative reproductive success), intra (within) and interspecific (between species) competition, energetics, predation, and parasitism could be included in models as well as anthropogenic components such as habitat degeneration, anthropogenic disturbance, hunting and fishing. At larger scale the change in numbers of separate but connected populations, through migration, form metapopulation dynamics.

As from a nature conservation point of view the purpose is to maintain or at least not critically endanger populations or species, locally and regionally. Along with an expected large expansion of the renewable industry concerns have be risen on the effect of a number of species and groups of organisms [2] and [3]. Therefore, and along with empirical field studies, predictive models have been used as a complement to direct observations and field studies. Whereas instrumentation can be used for monitoring both, physical and biological environment models, they are more specific, and here we describe examples of bio- ecological models only. The wind power development has resulted in the use of a number of different ecological models, and more recently also within marine energy, especially within the tidal power development. Early attempts of modelling in wave power projects have been conducted on biofouling impacts by [45]. From the experience of models used in connection with wind energy development we here describe models that have or most likely will be used within related future marine energy (wave and tidal) developments.

Why use models in conservation ecology and impact assessment of renewable energy projects whereas single projects or large scale (cumulative) impact? The short answer is that the use of models can be a complementary, cost effective tool in predicting outcomes of e.g. anthropogenic disturbances and when field studies are unrealistic in scale, cost or by ethical reasons. However, the use of models are unlikely to eliminate the use of traditional field survey methods, or the use of more modern technology which enable in situ observations. On the contrary, models will need input and feedback from traditional and direct methods, in order to be verified and refined.

A. Collision Risk Models

Collision Risk Models (CRM) were first developed by [46]–[49] for assessing collisions of birds with wind turbines. Later a number of additional models has been further developed reviewed by e.g. [50] and [51]. Here, models are anticipated as an alternative to, or the only way of assessing collision risk and their numbers, when other means of direct observations of collisions and their numbers are impossible.

Parameters typically included in bird CRM's are turbine data: height, swept area, rpm, wing tip speed, number of blades and chord data of the turbines (area). Some models include multiple turbines and some also include the tower structure (as many birds collide with that) in the model and park layout. Physical factors of importance that may be included are wind speed and direction. Ornithological data included may be densities, species size and shape, flight height and (relative) speed, and in some models angel of approach.

The recent development and deployment of tidal power devices has accentuated the use of CRM in marine energy projects, focusing on fish and marine mammals but also diving birds in high energy sites e.g. [52]–[57].

Parameter input into tidal collision models are similar to wind power related models including physical variables such as velocity, turbine information such as geometry and number of blades, rpm and wing tip speed. Biological variable input may include e.g. size, body shape, speed and angel of approach of organism but also behavioural variables such as occurrences (densities) of animals predation behaviour and grazing in risk zone areas and their movements, avoidance (attraction) behaviour for particular species etc. in order to estimate risk of collisions resulting in hits (injury) or deaths.

Examples of modified variants of CRM are the *Encounter Rate Models* (ERM) are [50], [55], [58] and for the *Exposure Time Population Model* (ETPM) [59]. Similar to CRM, but with origin from predator-prey models, ERM has been used in order to estimate the risk for marine mammals to collide with tidal turbines [57] and [58]. The ERM differ from CRM mainly by estimating the risk of encountering a rotating turbine, whereas CRM estimates the risk of an individual passing through a turbine becoming hit based on total number of passages [60]. By performing sensitivity test, i.e. testing models by varying parameter input in both ERM and CRM, [57] could show that ERM always had lower collision risk output than CRM, mainly due to different assumption in behaviour (avoidance distance) and dive patterns (U vs V-shaped dives) in harbour seals. Several later evaluations on the use of models [57] recommend alterations in model design in order to improve and make results more realistic. The ETPM model was developed in order to assess bird collisions with tidal turbines where bird behaviour (avoidance) around turbines is unknown.

B. Models for future marine energy project expansion

As the marine energy industry will grow and become industrial sized the employment of models focusing on extinction risks and covering larger scales will become more important.

Analysing effects of loss or removal of individuals, population viability, in certain species has led to the development of a number of demographic models. *Minimum Viable Population* analysis [61] was developed in order to understand critical population levels in endangered species, usually with aim of avoiding population genetic homogeneity. In order to find a tool for marine mammal management [62] developed a *Potential Biological Removal* (PBR) model. PBR has been used to analyse and estimate populations scale effects of displacement and computed collision mortality in birds from large scale (offshore) wind power development [63]–[65]. The aim of using PBR is to estimate population impact, including cumulative impacts, as if population number can be maintained or if a decline could be at hand as a result of anthropogenic activities. Process based models, such as *Individual Based Models* (IBM), or *Agent Based Models,* are dynamic models that consider a population as a collection of individuals but with different behaviour and morphology. IBM are for example used for predicting population responses from environmental changes, but also a large variety of other ecological sciences. Examples of the use of IBM include [66] who estimated the effect of habitat loss and disturbance on waders and waterfowl, and their behaviour, in relation to the planned Severn Barrage in southwest UK. IBM are commonly data hungry and could include data such energetics, budgeting, and thus food availability, and population dynamics among several parameters.

At larger scale particular habitats or even landscapes may be endangered. *Habitat use Models* (HuS), *Spatial Dynamic Models* (SDM), *Resource Selection Models* (RSM), *Ecosystem Based Models* (ESB) and *Ecological Network Analysis* (ENA) such as in [67] are examples.

HuS could be described as models trying to investigate suitable habitats based on known species requirements. Reference [68] used a presence-absence model in order to predict habitat use by two species of dolphins in the Bay of Biscay and the English Channel. Examples of SDM studies are [69] and [70] aiming at analysing the cumulative impact from land based wind parks on skylarks. Miller et al. 2014 [71] used a RSM in order to study the effect on golden eagles from large scale wind power development in the north-eastern USA. Finally, an example of ESB is [72] who analysed large scale ecosystem effects, altered sea-use patterns on marine biota, based on the ongoing and future development of offshore wind in the German North Sea.

C. How useful are models?

A common critique in the use of models, which ever, is the dependency of large number of data and information. Variables, important for population dynamics, may also be lacking completely. In reality, this may lead to a number of assumptions, and thereby, possible uncertainties may be added on top of each other, making conclusions unprecise or even incorrect. Additional ecological information, which may be of importance but not yet included in models, include sex and age differences which also reflect condition and experience. In general, such data is less common for marine animals as compared to avian information, although seldom adequate even there. Individual behaviour and its variation, including avoidance of ocean energy areas is another factor that may add complexity to models. The use of organism averages, deliberately or passively, is also likely occur at different number in/over given area due to e.g. (micro/meso) habitat heterogeneity or physical prerequisites.

Consequently, model outcomes must be tested against real world empirical data and thereafter adjusted [51], [73], but which may not have occurred yet in any project. Testing models with sensitivity analysis of ingoing parameters in model are therefore suggested, and to some extent done [51]. Testing model output could possibly be done in controlled experiments as testing in laboratory is possible, exemplified by [74] who empirically tested collisions risk in fish with turbines in semi natural conditions.

The use of models may also pinpoint areas of future focus, e.g. what data is needed to collect in order to improve models and their accuracy. More information from traditional sampling methods will help calibrate models. Also, newly "developed" technologies such as passive and active acoustic devices will add and chasten information to be fed into the use of models. Tagging, capture recapture, the use telemetry and GPS etc., are additional technologies which, directly and indirectly can feed information into models, and thus help to broaden our insight in the effects and impacts of MRE installations on the marine environment.

As mentioned in the beginning of this section, the use of models in theoretical evolutionary and population ecology, as well as for nature conservation purposes, is immense. The importance of the use of models is thus likely growing but, as pointed out by [75], must be communicated intelligently to the non-scientific community. As the marine energy sector development will continue to expand the coming decades, so will ecologist working with impacts of renewable energy need to use more and different models. An early use of models will also inspire the development of more refined models for the use in a development of sustainable marine energy sector.

V. Discussion, Conclusion and further needs

Environmental monitoring has a long history and takes an important role in the emerging renewable energy sector. Assessing and classifying the status of the habitat and located species is necessary to detect changes in the natural environment. With the rising renewable offshore technologies such as offshore wind power, but also wave and tidal power a new stressor is introduced in the already stressed marine environment [1]. Environmental impacts need to be detected early to provide a chance for mitigation during all phases of deployment and operation.

Several factors determine the choice of monitoring methods, technologies and models. This may include the introduced stressor such as the deployed renewable energy device, the receptor like species, populations, habitats or the physical environment. Besides mentioned factors, country specific regulatory frameworks determine the choice of methodologies and sampling tools. On the background of spatial and temporal variation and the individual economical capability of the project, complexity of the subject becomes apparent.

Applying the same renewable energy devices can result in different threats depending on the geographical area due to other initial situations and species composition. Different methods used for the same target species might show dissimilar results. Keeping this in mind accentuates the importance for balanced selection of methods [20].

The target species or habitat plays a main role determining the methods. An extensive data collection of before and after impact assessment only does not ensure that environmental changes will be noted. Therefore, additional studies that look at rates of change and gradients in population and habitat size help to clear trends, even when absolute changes cannot be detected [4]. Extreme value analysis, used to model the probability and periodicity of extreme values, which are rare values in the tail of a probability distribution, can refine interpreting the collected data [76].

Multidimensionality of factors such as stressor, receptor, the variety of technologies, and models on a temporal and spatial background illustrates the complexity of the MRE monitoring subject. In spite of this complexity there is a need for more standardized methods in data acquisition and analysis. Cooperation and initiatives such as Triton is an example to facilitate and routinize the environmental monitoring practice and connecting involved parties [77].

Traditional methods stand out with long sampling experience but are often destructive for habitats or species. Modern methods such as platforms with multi parameter equipment and the use of deterministic models established a new generation of beneficial and advantageous monitoring analyses. However, modern methods and models often rely on data of traditional sampling to verify their results and feed models with additional information. Further research and development for optimization and a further application of both, traditional and modern methods to maximize the output and complement each other are indispensable in environmental monitoring of marine renewable energies.

Acknowledgment

This Project received funding from the Swedish Energy Agency, the Swedish Research Council Formas and from the European Union´s Seventh Framework Programme for research, technological and demonstration under grant agreement no 607656. We would like to thank 2 reviewers for constructive comments that greatly improved the manuscript.

References

[1] L. Hammar, M. Gullström, T. G. Dahlgren, M. E. Asplund, I. Braga Goncalvese, S. Molander, "Introducing ocean energy industries to a busy marine environment," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 178-185, Jan. 2017.

[2] R. Inger, M. J. Attrill, S. Bearhop, A. C. Broderick, W. J. Grecian, D. J. Hodgson, C. Mills, E. Sheehan, S. C. Votier, M. J. Witt, B. J. Godley, "Marine renewable energy: potential benefits to biodiversity? An

urgent call for research," *Journal of Applied Ecology*, vol. 46, pp. 1145–1153, 2009.
[3] O. Langhamer, K. Haikonen, J. Sundberg, "Wave power—Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1329–1335, 2010.
[4] A. Copping, N. Sather, L. Hanna, J. Whiting, G. Zydlewsk, G. Staines, A. Gill, I. Hutchison, A. M. O'Hagan, T. Simas, J. Bald, C. Sparling, J. Wood, E. Masden, "Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renew- able Energy Development Around the World," State of the Science Report Annex IV, 2016.
[5] H. L. Rees, S. E. Boyd, C. Brown, D. S. Limpenny, W. Meadows, K. M. Cooper, J. Rees, C. Mason, M. Schratzberger, "Guidelines for the conduct of benthic studies at aggregate dredging sites," The Centre for Environment, Fisheries and Aquaculture Science (CEFAS), Burnham Laboratory, 2002.
[6] A. Judd, "Guidelines for data acquisition to support marine environmental assessments for offshore renewable energy projects," Centre for Environment, Fisheries & Aquaculture Science, Cefas contract Rep. ME5403 – Module 15, 2012.
[7] (2017) The OSIL website. [Online]. Available: http://www.osil.co.uk/Home.aspx
[8] D. Gong, N. Zhang, Y. Liu, X. Li, P. Talalay, "Small-diameter vibrocorer for sediment coring beneath Antarctic ice shelves: General concept and testing," *Ocean Engineering*, vol. 126, pp. 232–239, 2016.
[9] E. Anastasios, *Methods for the Study of Marine Benthos*, 4th ed., E. Anastasios, Ed., John Wiley and Sons, Ldt. 2013.
[10] W. H. Hubert, K. L. Pope, J. M. Dettmers, Passive Capture Techniques, A. V. Zale, T. M. Sutton, D. L. Parrish, Ed., *Fisheries Techniques*, 3rd ed., American Fisheries Society, Bethesda, Maryland, 2013.
[11] M. Lake, "Freshwater fish: passive nets- fyke nets,"Department of Conservation Te Papa Atawhai, Inventory and monitoring toolbox: freshwater fish DOCDM-997948, 2013.
[12] M. Prchalová, J. Kubečka, M. Říha, T. Mrkvička, M. Vašek, T. Jůza, M. Kratochvíl, J. Peterka, V. Draštík, J. Křížek, "Size selectivity of standardized multimesh gillnets in sampling coarse European species," *Fisheries Research*, vol. 96, pp. 51–57, 2009.
[13] O. Langhamer, H. Holand, G. Rosenqvist, "Effects of an Offshore Wind Farm (OWF) on the Common Shore Crab Carcinus maenas: Tagging Pilot Experiments in the Lillgrund Offshore Wind Farm (Sweden)," *PLoS ONE*, vol. 11(10), e0165096, 2016.
[14] M. S. Love, M. M. Nishimoto, S. Clark, A. Scarborough Bull, "Identical Response of Caged Rock Crabs (Genera Metacarcinus and Cancer) to Energized and Unenergized Undersea Power Cables in Southern California, USA," *Bull. Southern California Acad. Sci.*, vol. 114(1), pp. 33–41, 2015.
[15] J. Nedwell, A. Turnpenny, J. Langworthy, B. Edwards, "Measurements of underwater noise during piling at the Red Funnel Terminal, Southampton, and observations of its effect on caged fish," Subacoustech Ltd, Rep. Ref.: 558 R 0207, 2003.
[16] K. Macleod, S. Du Fresne, B. Mackey, C. Faustino, I. Boyd, "Approaches to marine mammal monitoring at marine renewable energy developments," SMRU Limited Consulting, Final Report, Ref. MERA 0309 TCE, 2010.
[17] M. J. Brandt, A.-C. Dragon, A. Diederichs, A. Schubert, V. Kosarev, G. Nehls, V. Wahl, A. Michalik, A. Braasch, C. Hinz, C. Ketzer, D. Todeskino, M. Gauger, M. Laczny, W. Piper, " Effects of offshore pile driving on harbour porpoise abundance in the German Bight Assessment of Noise Effects," Final Report Prepared for Offshore Forum Windenergie, 2016.
[18] G. Bradbury, M. Trinder, B. Furness, A. N. Banks, R. W. G. Caldow, D. Hume, "Mapping Seabird Sensitivity to Offshore Wind Farms," *PLoS ONE*, vol. 9(9), e106366, 2014.
[19] T. G. Dahlgren, M.-L. Schläppy, A. Šaškov, M. H. Andersson, Y. Rzhanov, I. Fer, *Marine Renewable Energy Technology and Environmental Intractions*, M. A. Shields, A. I. L. Payne, Ed., Springer Science +Buisness Media Dordrecht, 2014.
[20] D. J. McCauley, K. A. McLean, J. Bauer, H. S. Young, F. Micheli, "Evaluating the performance of methods for estimating the abundance of rapidly declining coastal shark populations," *Ecological Applications*, vol. 22(2), pp. 385–392, 2012.
[21] G. D. Hastie, D. M. Gillespie, J. C. D. Gordon, J. D J. Macaulay, B. J. McConnell, C. E. Sparling, *Marine Renewable Energy Technology and Environmental Intractions*, M. A. Shields, A. I. L. Payne, Ed., Springer Science +Buisness Media Dordrecht, 2014.
[22] C. Stenberg, M. van Deurs, J. Støttrup, H. Mosegaard, T. Grome, G. Dinesen, A. Christensen, H. Jensen, M. Kaspersen, C. Willestofte Berg, S. B. Leonhard, H. Skov, J. Pedersen, C. B. Hvidt, M. Klaustrup, "Effect of the Horns Rev 1 Offshore Wind Farm on Fish Communities Follow-up Seven Years after Construction," DTU Aqua, National Institute of Aquatic Resources, DTU Aqua Rep. No. 246-2011, 2011.
[23] M. H. Andersson, M. Gullström, M. Asplund, "Importance of Using Multiple Sampling Methodologies for Estimating of Fish Community Composition in Offshore Wind Power Construction Areas of the Baltic Sea," *AMBIO A Journal of the Human Environment*, vol. 36(8), pp. 634-636, Jan. 2008.
[24] O. Langhamer, D. Wilhelmsson, "Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes – A field experiment," *Marine Environmental Research*, vol. 68, pp. 151–157, June 2009.
[25] S. B. Leonhard, J. Pedersen, "Benthic Communities at Horns Rev Before, During and After Construction of Horns Rev Offshore Wind Farm," Vattenfall, Bio/consult as, Final Report, Annual Report, 2005.
[26] J. T. Reubens, S. Degraer, M. Vincx, "Aggregation and feeding behaviour of pouting (Trisopterus luscus) at wind turbines in the Belgian part of the North Sea," *Fisheries Research*, vol. 108, pp. 223–227, 2011.
[27] S. A. Bortone, M. A. Samoilys, P. Francour, Fish and macroinvertebrate evaluation, W. Seaman Jr., Ed., *Artificial reef evaluation with application to natural marine habitats*, Boca Raton, Fla. CRC Press, 2000.
[28] D. K. Mellinger, K. M. Stafford, S. E. Moore, R. P. Dziak, H. Matsumoto. "An overview of fixed passive acoustic observation methods for cetaceans," *Oceanography*, vol. 20(4), pp. 36–45, 2007.
[29] C. C. Eriksen, T. J. Osse, R. D. Light, T. Wen, T. W. Lehman, P. L. Sabin, J. W. Ballard, A. M. Chiodi, "Seaglider: A long-range autonomous underwater vehicle for oceanographic research," *IEEE J Oceanic Eng.,* vol. 26, pp. 424-436, 2001.
[30] D. L. Rudnick, R. E. Davis, C. C. Eriksen, D. M. Fratantoni, "Underwater Gliders for Ocean Research," *Marine Technology Society Journal*, vol. 38(1), pp. 48–59, 2004.
[31] F. Francisco, J. Sundberg, "Sonar for Environmental Monitoring: Understanding the Functionality of Active Acoustics as a Method for Monitoring Marine Renewable Energy Devices," in *EWTEC Proc.* 2015, paper 07P2-3.
[32] M. Bevelhimer, C. Scherelis, J. Colby, C. Tomichek, M. Adonizio, "Fish Behavioral Response during Hydrokinetic Turbine Encounters Based on Multi-Beam Hydroacoustics Results", *3rd Marine Energy Technology Symposium (METS)*, Washington DC, USA, 2015.
[33] G. Staines, H. Zydlewski, H. Viehman, H. Shen, J. McCleave, "Changes in vertical fish distributions near a hydrokinetic device in Cobscook Bay, Maine, USA,". in *EWTEC Proc.* 2015, paper 9A4-4.
[34] B. Williamson, P. Blondel, E. Armstrong, P. Bell, C. Hall, J. Waggitt, B. Scott, "A Self-Contained Subsea Platform for Acoustic Monitoring of the Environment Around Marine Renewable Energy Devices - Field Deployments at Wave and Tidal Energy Sites in Orkney, Scotland," *Journal of Oceanic Engineering*, vol. 41(1), pp. 67-81, 2016.
[35] C. Albaladejo, F. Soto, R. Torres, P. Sánchez, J. A. López, "A Low-Cost Sensor Buoy System for Monitoring Shallow Marine Environments," *Sensors*, vol. 12, pp. 9613-9634, 2012.
[36] J. A. Kington, F. Selinger, "The development and use of weather buoys 1940–2005," *Weather*, vol. 61-6, 2006.
[37] K. Nittis, C. Tziavos, R. Bozzano, V. Cardin, Y. Thanos, G. Petihakis, M. E. Schiano, F. Zanon, "The M3A multi-sensor buoy network of the Mediterranean Sea," *Ocean Sci.*, vol. 3, pp. 229–243, 2007.
[38] R. W. McFarlane, J. Lester, "Determination of Seabird Density using Marine Radar," in Proceedings, International Conference and Workshop on Radar Ornithology and Entomology, 25-28 June, 2007, Helgoland, Germnay.
[39] R. W. McFarlane, L. J. Lester. "Determination of nearshore seabird density on the upper Texas coast," Bird Mortalities Risk Assessment, 2005.

[40] R. W. McFarlane, "Toward prediction of bird-rotor collision mortality," in Proc. NWCC, Wildlife Workgroup Research Planning Meeting VI, 2007.

[41] G. Dell'Omo, "Radar Aeroecology Applications and Perspectives," in *Conference Proceedings*, Rome, 2017.

[42] (2017) The Unmanned Systems Technology website. [Online]. Available: http://www.unmannedsystemstechnology.com/2017/04/new-unmanned-undersea-robot-hunts-invasive-lionfish/

[43] (2017) The FORCE website. [Online]. Available: http://fundyforce.ca/environment/

[44] F. G. A. Francisco, "Sonar for environmental monitoring of marine renewable energy technologies," Licentiate Thesis, Division of Electricity, Uppsala University, 2016.

[45] O. Langhamer, D. Wilhelmsson, J. Engström, "Artificial reef effect and fouling impacts on offshore wave power foundations and buoys – a pilot study," *Estuarine Coastal and Shelf Science*, vol. 82, pp. 426-432, 2009.

[46] V. Tucker, "Using a Collision Model to Design Safer Wind Turbine Rotors for Birds," *Journal of Solar Energy Engineering*, vol. 118(4), pp. 263-269, 1996.

[47] V. Tucker, "A Mathematical Model of Bird Collisions with Wind Turbine Rotors," *Journal of Solar Energy Engineering*, vol. 118(4), pp. 253-262, 1996.

[48] W. Band, "Windfarms and Birds: Calculating a Theoretical Collision Risk Assuming No Avoiding Action," Scottish Natural Heritage Report, pp. 1-10, 2000.

[49] W. Band, M. Madders, D. P. Whitfield, Developing field and analytical methods to assess avian collision risk at wind farms, M. de Lucas, G. F. E. Janss, M. Ferrer, Ed. *Birds and Wind Farms: Risk Assessment and Mitigation,* Madrid, Quercus, pp. 259–275, 2007.

[50] M. Lonergan, D. Thompson, "Collision Risk and Impact Study: Examination of Models for Estimating the Risk of Collisions Between Seals and Tidal Turbines," Report by Sea Mammal Research Unit (SMRU), MR7.2.2, pp. 1-15, 2015.

[51] E. Masden, A. Cook, "Avian Collision Risk Models for Wind Energy Impact Assessments," *Environmental Impact Assessment Review*, vol. 56, pp. 43-49, 2016.

[52] P. Romero-Gomez, M. Richmond, "Discrete Element Modeling of Blade-Strike Frequency and Survival of Fish Passing Through Hydrokinetic Turbines," in *Proceedings 2nd Energy Technology Symposium*, April 15-18, 2014, Seattle, WA, USA.

[53] L. Hammar, L. Eggertsen, S Andersson, J. Ehnberg, R. Arvidsson, M. Gullström, S. Molander, "A Probabilistic Model for Hydrokinetic Turbine Collision Risks: Exploring Impacts on Fish," *Plos One*, vol. 10(3), pp. 1-25, 2015.

[54] B. Band, C. Sparling, D. Thompson, J. Onoufriou, E. San Martin, N. West, "Refining Estimates of Collision Risk for Harbour Seals and Tidal Turbines, " Report by ABP Marine Environmental Research Ltd (ABPmer), Sea Mammal Research Unit (SMRU), and SMRU Consulting, pp. 1-133, 2016.

[55] W. Band, "Assessing Collision Risk between Underwater Turbines and Marine Wildlife," Report by Scottish Natural Heritage, pp. 1-93, 2016.

[56] D. Thompson, J. Onoufriou, A. Brownlow, C. Morris, "Data Based Estimates of Collision Risk: An Example Based on Harbour Seal Tracking Data around a Proposed Tidal Turbine Array in the Pentland Firth," 900 edn, Scottish Natural Heritage, pp. 1-41, 2016.

[57] J. Wood, R. Joy, C. Sparling, "Harbor Seal - Tidal Turbine Collision Risk Models. An Assessment of Sensitivities," Report by SMRU Consulting. pp. 1-57, 2016.

[58] B. Wilson, R. S. Batty, F. Daunt, C. Carter, "Collision risks between marine renewable energy devices and mammals, fish and diving birds," Report to the Scottish Executive by the Scottish Association for Marine Science, 2007.

[59] M. Grant, M. Trinder, N. Harding, "A Diving Bird Collision Risk Assessment Framework for Tidal Turbines," Report by RPS group, pp. 1-38, 2014.

[60] B. Band, "Using a Collision Risk Model to Assess Bird Collision Risks for Offshore Wind Farms," Report by British Trust for Ornithology (BTO), Bureau Waardenburg bv and University of St Andrews, pp. 1-62, 2012.

[61] M. L. Shaffer "Minimum population sizes for species conservation," American Institute of Biological Sciences, vol. 31 (2), pp. 131–134, 1981.

[62] B. L. Taylor, P. R. Wade, D. P. De Master, J. Barlow, "Incorporating uncertainty into management models for marine mammals," *Conserv. Biol*., vol. 14, pp. 1243–1252, 2000.

[63] J. Diffendorfer, J. Beston, M. Merrill, J. Stanton, M. Corum, S. Loss, W. Thogmartin, D. Johnson, R. Erickson, K. Heist, A Method to Assess the Population-Level Consequences of Wind Energy Facilities on Bird and Bat Species, J. Köppel, Ed., *Wind Energy and Wildlife Interactions*, pp. 65-76, Springer, 2017.

[64] M. Busch, S. Garthe, "Approaching Population Thresholds in Presence of Uncertainty: Assessing Displacement of Seabirds from Offshore Wind Farms," *Environmental Impact Assessment Review*, vol. 56, pp. 31-42, 2016.

[65] M. Leopold, M. Boonman, M. Collier, N. Davaasuren, R. Fijn, A. Gyimesi, J. de Jong, R. Jongbloed, B. Poerink, K. Krijgsveld, S. Lagerveld, R. Lensink, M. Poot, J. van der Wal, M. Scholl, "Framework for Assessing Ecological and Cumulative Effects of Offshore Wind Farms: A First Approach to Deal with Cumulative Effects on Birds and Bats of Offshore Wind Farms and Other Human Activities in the Southern North Sea," Report by IMARES - Wageningen UR, pp. 1-360, 2015.

[66] A. West, R. Caldow, "The Development and Use of Individuals-Based Models to Predict the Effects of Habitat Loss and Disturbance on Waders and Waterfowl," *Ibis*, vol. 148, pp. 158-168, 2006.

[67] A. Raoux, S. Tecchio, J.-P. Pezy, G. Lassalle, S. Degraer, D. Wilhelmsson, M. Cachera, B. Ernande, C. Le Guen, M. Haraldsson, K. Grangeré, F. Le Loc´h, J.-C. Dauvin, N. Niquil, "Benthic and fish aggregation inside an offshore wind farm: Which effects on the trophic web functioning?," *Ecological Indicators*, vol. 72, pp. 33-46, 2017.

[68] A. Virgili, M. Racine, M. Authier, P. Monestiez, V. Ridoux, "Comparison of habitat models for scarcely detected species," *Ecological Modelling*, vol. 346, pp. 88-98, 2017.

[69] R. Bastos, A. Pinhanços, M. Santos, R. Fernandes, J. Vicente, F. Morinha, J. Honrado, P. Travassos, P. Barros, J. Cabral, "Evaluating the Regional Cumulative Impact of Wind Farms on Birds: How can Spatially Explicit Dynamic Modelling Improve Impact Assessments and Monitoring?," *Journal of Applied Ecology*, vol. 53, pp. 1330-1340, 2015.

[70] M. Santos, R. Bastos, D. Ferreira, A. Santos, P. Barros, P. Travassos, D. Carvalho, C. Gomes, H. M. Vale-Gonçalves, L. Braz, "A spatial explicit agent based model approach to evaluate the performance of different monitoring options for mortality estimates in the scope of onshore windfarm impact assessments," *Ecological Indicators,* vol. 73, pp. 254-263, 2017.

[71] T. Miller, R. Brooks, M. Lanzone, D. Brandes, J. Cooper, K. O'Malley, C. Maisonneuve, J. Tremblay, A. Duerr, T. Katzner, "Assessing Risk to Birds from Industrial Wind Energy Development via Paired Resource Selection Models," *Conservation Biology*, vol. 28, pp. 745-755, 2014.

[72] B. Burkhard, S. Opitz, H. Lenhart, K. Ahrendt, S. Garthe, B. Mendel, W. Windhorst, „Ecosystem Based Modeling and Indication of Ecological Integrity in the German North Sea - Case Study Offshore Wind Parks," *Ecological Indicators*, vol. 11(1), pp. 168-174, 2009.

[73] E. Masden, "Developing an Avian Collision Risk Model to Incorporate Variability and Uncertainty," Report by University of the Highlands and Islands (UHI), pp. 1-47, 2015.

[74] S. Amaral, M. Bevelhimer, G. Cada, D. Giza, P. Jacobson, B. McMahon, B. Pracheil, "Evaluation of Behavior and Survival of Fish Exposed to an Axial-Flow Hydrokinetic Turbine," *North American Journal of Fisheries Management*, vol. 35(1), pp. 97-113, 2015.

[75] S. J. Cartwright, K. M. Bowgen, C. M. Collop, K. Hyde, J. Nabe-Nielsen, R. Stafford, R. Stillman, R. B. Thorpe, R. M. Sibley, "Communicating complex ecological models to non-scientist end users," *Ecol. Modelling*, vol. 338, pp. 51-59, 2016.

[76] L. E. Wiesebron, J. K. Hornea, A. N. Hendrix, "Characterizing biological impacts at marine renewable energy sites," *International Journal of Marine Energy*, vol. 14, pp. 27–40, 2016.

[77] (2017) The Triton website. [Online]. Available: https://triton.labworks.org/