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Article

Comparability of Outputs between Traditional and Simulation-Based Approaches to Collision Risk Modelling

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Abstract: Tidal stream energy is a predictable renewable energy source; however, environmental consent of developments remains a key barrier to the expansion of this industry. Uncertainty around collision risk, i.e., the risk of animals colliding with a tidal device, remains a major barrier to consent. Collision risk models are used in environmental impact assessments. Common collision risk models, like the Encounter Rate and Band Models, have limitations in accommodating new device designs and flexibility. To address this, a simulation-based approach was developed. To provide confidence in its use, it is important that the simulation-based approach is compared against the Band model and the Encounter rate model, which have been regularly used in the UK. Here, we compared collision risk estimates from the three models under the same exact conditions and one alternative condition. The results of the main scenario (where all conditions were the same) showed that the three models produced comparable results with <6% difference across all models. However, for the alternative scenario, the simulation-based approach produced a result three times higher compared to other models, which could not account for a vertical approach angle. These findings provide confidence in the simulation-based approach whilst also outlining the importance of selecting an appropriate collision risk model, tailored to the specific assessment scenario. Improved understanding and application of such models hold the key to more accurate risk evaluations in environmental impact assessments, thus facilitating the sustainable development of the tidal energy industry.

Keywords: collision risk model; environmental impacts; tidal turbines; marine energy

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1. Introduction

Achieving global net zero carbon emissions requires a mix of renewable energy sources, including marine tidal energy [1]. With an abundant tidal energy resource, such as that available in the UK and Canada, tidal energy converters (TECs; Table 1) can provide a predictable source of renewable energy for centuries [2]. While several TECs, and more recently, even the first small arrays (~4–6) [3,4], have been installed, the tidal energy industry will need to install larger arrays of devices to contribute significantly to the renewable energy mix [2,5]. Tidal energy sites often coincide with important habitats for many species such as fish, cetaceans, pinnipeds, and birds [6–8]. It is therefore important to understand the interactions between arrays of TECs and wildlife, particularly with regard to collision risk, i.e., the risk of animals colliding with the moving parts of a TEC [8]. Collision risk is a main hurdle to the consenting of TECs [5] with uncertainty around key factors such as avoidance and evasion, which are extremely important parameters when assessing collision risk [5]. Furthermore, with few operational TECs to learn from about collision risk, the industry challenge consists of providing robust scientific evidence of their impact on the environment to the point where regulatory bodies have the confidence to consent to larger arrays of devices.

Table 1. List and definitions of acronyms used throughout the paper.

Acronym	Definition
TEC	Tidal energy converter
EIA	Environmental impact assessment
CRM	Collision risk model
ERM	Encounter rate model
SBA	Simulation-based approach
HATT	Horizontal axis tidal turbine
VATT	Vertical axis tidal turbine
CR	Collision risk estimate
CP	Collision probability
SA	Swept Area

Typically, an environmental impact assessment (EIA) is required before TEC can be installed to quantify the risk to receptors of interest and outline potential mitigation measures if needed [9]. Ultimately, the EIA aids regulators during the decision-making process, with respect to consent for the project and on what conditions. Tidal projects such as the SeaGen installation in Northern Ireland [10] and the MeyGen development in Scotland [3] required extensive EIAs and research studies as they were two of the first tidal energy projects to be connected to the grid, and as such, regarded as pioneering projects. For MeyGen, the EIA also required an assessment of collision risk for receptors of interest (e.g., marine mammals) [3]. To give an estimate of the collision risk posed by TECs, in terms of a predicted number of animals for a given time period (e.g., year), a collision risk model was used [3,8,11]. A collision risk model (CRM) requires information on the animal such as swim speed, size, behavior, and abundance in the area (typically density), in addition to information on the TEC design and operation. In simplified terms, CRMs use this information to estimate the number of collisions likely to occur over an operational period. How this information is used in calculating the estimated number of collisions varies among the different CRMs in use.

The Band model is a commonly used CRM that was first developed in 2000 for estimating risk for wind turbines and birds [12] and has since been adapted to estimate collision risk for TECs [11]. The model uses a formula-based approach to estimate a collision rate from the risk of collision from a single animal transit scaled by the predicted number of transits over a given period. The risk of collision from a single transit, referred to herein as collision probability, is calculated under the assumption that the animal is moving at a horizontal trajectory, taking into account the rotor blade profiles and the speeds of the animal and rotor to produce a probability. The collision probability is then scaled using the local density of animals and their transit rate through the swept area of the TEC, which produces a number of collisions over time. The application of the Band model is constrained to horizontal axis tidal turbines (HATT) and has been used in several EIAs for TECs [13–15]. The Band model has also been used in a research capacity [16] to investigate the efficacy of additional data sources such as information on seal mortality [17] and seal tagging data [16].

The other commonly used CRM for TECs is the Encounter Rate Model (ERM), which was adapted from a predator–prey model [8]. The ERM estimates collision risk by calculating the volume swept by the TEC (predator) and the local density of animals (prey) in the area, as opposed to the probability of collision from a single transit, as in the Band model. By estimating collision risk by calculating the volume of area swept by the TEC, the

ERM assumes an equal chance of collision from all angles. The ERM can be applied to both HATT [8,11,18] and vertical axis tidal turbines (VATT) [13] and has been used in multiple EIAs for tidal devices [3,4,13,15] and in research [18].

Another CRM, the simulation-based approach (SBA), was developed to estimate the collision risk for novel device designs; specifically, a tidal kite [19]. The SBA model was further developed to use the 3D open-source modeling software Blender [20] to simulate the shape and movement of a TEC and animal over time and over many simulations from which a collision probability is calculated. The SBA can be performed for any device design and, in addition, allows for any angle of approach to be defined [21]. The SBA uses similar information to the Band model and ERM; however, outputs are more detailed, such as the different probabilities of collision over the swept area of the TEC [21]. Additionally, the model can also extract information such as the relative speed of each individual collision and the location of that collision on both the animal's body and the device, which is valuable information when estimating the likelihood of mortality [22]. The SBA therefore offers potential advantages in scenarios where more detail in collision risk estimates is needed by allowing the user to address a range of collision risk scenarios and parameters for animals and TECs.

Previously, the Band model and ERM have been compared [11] to ensure similar probabilities and to provide standard parameters for use in assessments. It is likely that for single or very small-scale arrays of HATT or VATT, these approaches may be sufficient, particularly where consideration is given to the assessment being proportionate to the risk. However, for the industry to move ahead, new tools such as the SBA may be required to determine the potential of collision risk with larger arrays and/or a range of novel device designs. It is therefore important to provide a comparison of the SBA against the Band model and ERM, as a form of validation, in so far as providing confidence that it produces equivalent or comparable results in the same scenarios.

The objective of this paper was to compare collision risk estimates produced using the SBA to those of the Band model and ERM under the same conditions and one alternative set of conditions. Furthermore, through the results and discussion, we aimed to highlight the differences and similarities across the outputs from the three models.

2. Materials and Methods

To provide a comparison of the CRMs, two collision risk estimates are provided. The first is an estimate for the harbor seal (Phoca vitulina) and is produced using the Falls of Warness example, which is outlined in the Scottish Natural Heritage Guidance Note on tidal energy collision risk [11], referred to herein as the 'guidance note'. The number of harbor seals estimated to collide with a TEC per year is calculated using the SBA, and the results are compared to those of the Band model and ERM from the same example. The second estimate is produced for an alternative scenario, where a vertical angle of approach was used for further comparison of the SBA to the Band model and ERM. The example and alternative scenarios were chosen to provide consistency in input parameters and allow a direct comparison, whilst drawing on an accepted comparison of the Band and ERM as outlined in the guidance note [11].

2.1. Simulations

The SBA produces collision probabilities with simulations of the 3D shape and movement of a TEC and animal. The model runs 1000 s of simulations using a grid of animal starting positions, and for each animal starting position, multiple repeated device starting rotations (i.e., time lags). By performing the 1000 s of simulations for the range of starting positions, a collision probability can be calculated for the swept area of the TEC. This is achieved by the model detecting the collisions and outputting where on the TEC that collision occurs. The number of collisions detected is then divided by the total number of possible collisions (i.e., the number of starting positions for that grid position) to produce the probability of collision for a single transit, i.e., the collision probability. Further details on the simulations, convergence studies, and the overall development of the SBA can be found in the literature [21].

To produce collision risk estimates, the collision probabilities produced from the SBA must be scaled using the number of likely transits to occur past the swept area of the TEC. This can be achieved by adapting the method used for estimating the number of transits through the swept area for the Band model, as described in the guidance note [11], where the number of transits over the operational time is calculated as:

$$Nt = D \times SA \times v \times t \tag{1}$$

where Equation (1) calculates the number of transits (Nt) through the swept area by multiplying the density of animals (D) in the area by the swept area (SA), the animal approach speed (v), and the time the TEC is expected to be in operation (t).

To calculate the collision risk estimate (CR) (Equation (2)), the number of transits is multiplied by the collision probability (CP) produced by the simulations, giving an estimate of the number of collisions for the operational time used. All estimates produced are non-avoidance collision estimates, i.e., they do not incorporate avoidance behavior.

$$Collision\ risk\ estimate = Nt \times CP \tag{2}$$

2.2. Falls of Warness Example

To facilitate a directly comparable set of results from the SBA to results from the Band model and the ERM, the guidance note example, Falls of Warness, was used [11]. This example is from an assessment at the European Marine Energy Centre tidal test site, Orkney, UK, which used empirical wildlife survey data from the site between 2005 and 2014, where the harbor seal was the species of interest. The example calculates risk using a three-bladed rotor design and uses mean values for animal swim speed and flow speed, irrespective of the flow direction; full details of the example can be found in the guidance note [11]. Simulations for the SBA model were run using input parameters outlined in this example (Table 2), and the results for the Band model and ERM are taken directly from the previously published example for comparison.

Table 2. Parameters from the Falls of Warness example [11], the symbols, their units and values, and the stage in which they are used in the model (i.e., used in the simulation stage and/or in Equation (1)).

Input	Symbol	Unit	Value	Use
Animal length	L	m	1.41	Simulation
Number of blades	b	-	3	Simulation
Rotational speed	Ω	rpm	6.95	Simulation
Maximum blade width	Ω	m	1.5	Simulation
Blade profile	c/C	-	Table 2	Simulation
Blade pitch at tip	y	degrees	5	Simulation
Animal approach speed	v	ms^{-1}	1.82	Simulation/Equation (1)
Animal width	W	m	0.34	Simulation/Equation (1)
Rotor radius	R	m	12.5	Simulation/Equation (1)
Animal density	D	animals m^{-3}	3.33×10^{-10}	Equation (1)
Operational Time	t	s	3.906×10^{6}	Equation (1)

To produce a collision probability using the SBA, the input parameters from the worked example were used in the simulation stage and/or in Equation (1), as outlined in Table 2. Animal approach speed is used as an input parameter for simulating an animal approaching the TEC and is also used in Equation (1) to calculate the number of transits through the swept area. Similarly, animal width and rotor radius are used in both stages, as the physical shapes of the animals are simulated and used in Equation (1) when calculating the area that the animal and rotor occupy.

To run the SBA model for the example, a 3D shapefile for the rotor matching the device specifications was required. This was produced with the blade information provided in the guidance note [11] and consisted of the rotor radius (e.g., length of the blade), the maximum blade width, the number of blades and the blade pitch at the tip (Table 2), and the blade profile (Figure 1 and Table 3) and did not include a refinement for blade twist [11]. A single blade was produced using these characteristics in the open-source computer-aided design software FreeCAD [23], which was then imported into Blender [20], another open-source CAD software package, to be transformed into a rotor by making three copies of the blade and connecting them, equally spaced, at the base.

The parameters for each simulation to be used In Blender are supplied via input files, which were created to include the animal width, approach speed, and length (Table 2). The animal angle of approach for these simulations was horizontal, i.e., perpendicular to the rotor, which is the same as in the Band model [11]. In calculating a collision probability, a 26 m, 1 m by 1 m grid of starting positions was used, with 50 time lags for each starting position. This created a total of 36,450 simulations with 729 starting positions. Further details on time lags, grid size, and convergence studies can be found in Horne et al. (2021) [21].

After all simulations were completed, collision probabilities were calculated from the model outputs using R [24] and the 'plyr' package [25]. The collision probabilities were then used with Equations (1) and (2) to produce collision risk estimates with respect to the number of seals estimated to collide with the TEC per year.

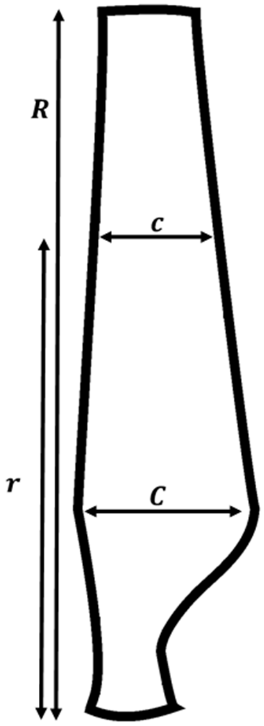

Figure 1. A schematic of the tidal turbine blade with the rotor with a radius R the length of the blade and r the distance along the blade. The chord (c) is the width of the blade at that point with C being the max chord length.

Table 3. Values for producing the blade profile used in the Falls of Warness example; the position along the blade is r/R and the blade chord (c) is a proportion of the maximum blade chord (C); table replicated from the guidance note [12].

*r***/***R*	*c***/***C*
0	0.690
0.050	0.730
0.100	0.790
0.150	0.880
0.200	0.960
0.250	1.000
0.300	0.980
0.350	0.920
0.400	0.850
0.450	0.800
0.500	0.750
0.550	0.700
0.600	0.640
0.650	0.580
0.700	0.520
0.750	0.470
0.800	0.410
0.850	0.370
0.900	0.300
0.950	0.240
1.000	0.000

2.3. Alternative Scenario: Vertical Approach Angle

An alternative scenario was run for the SBA where starting positions were directly above the rotor, such that the angle of approach was vertical to the TEC (Figure 2). All other parameters of the scenario remained the same. The angle of approach is likely to differ within and across species, depending on the context, situation, and/or environment. Therefore, this scenario was run to demonstrate the difference between ecologically possible and contrasting scenarios to the horizontal angle of approach. This provides a comparison against the Band and ERM, where the Band model cannot adapt the angle of approach and the ERM assumes an equal chance of collision from all angles. Varying one parameter where all others remain the same allows a direct comparison of the influence of that parameter within the SBA and across the Band model and ERM. Results were processed using the same methods as described above to produce collision probabilities and collision risk estimates.

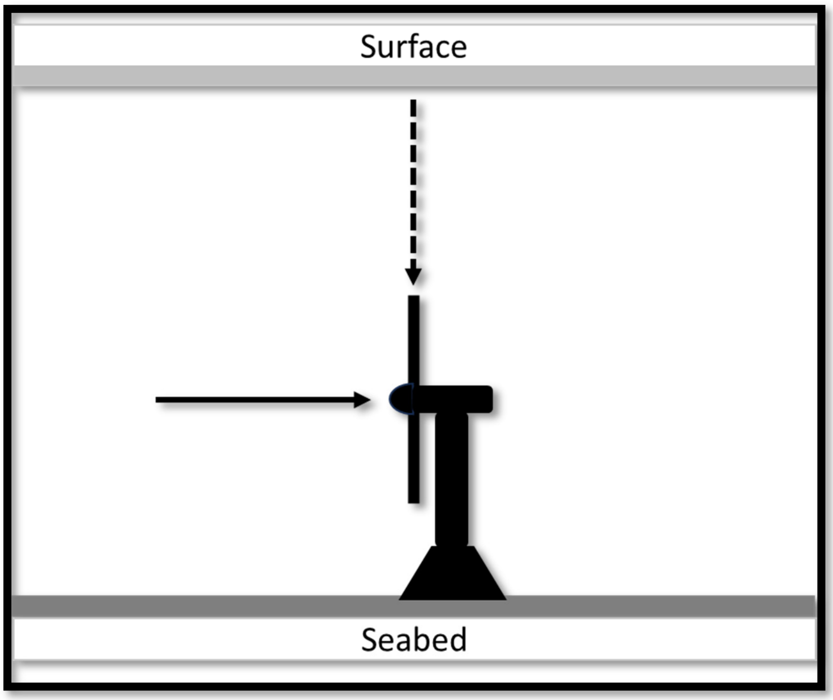

Figure 2. Diagram demonstrating the two approach angles assessed, the horizontal approach (solid arrow) and vertical approach (dashed arrow) in relation to the surface, seabed, and the TEC.

2.4. Comparison of Model Outputs

For all models run, collision risk estimates were calculated. For the Band and SBA models, collision probabilities were also produced (the ERM does not produce a collision probability as it calculates the volume of area swept by the turbine rather than the probability of collision for a single transit [11]). In addition, for the SBA, results for the vertical angle of approach were also presented; this was not possible for the Band model and ERM [11].

The results from each scenario and model are provided, whilst comparisons between the results were calculated. The differences were provided as percentages calculated using the difference between the target result and the SBA result divided by the SBA result and multiplied by 100. Differences were deemed acceptable if within similar ranges of difference to those of the Band and ERM (~5%) as described in the guidance note [11].

3. Results

For the horizontal angle of approach, the SBA calculated a collision probability of 0.3095 and a collision risk estimate of 2.61 seals per year. When compared to the results, the Band model and ERM provided a difference in collision risk estimates of 0.77% and 5.36%, respectively (Table 4). The collision risk estimate from the SBA was marginally higher than the Band model and ERM. Comparing the collision probability from the SBA model to the Band model (Table 4) produced a 0.58% difference.

The vertical approach scenario produced a collision probability three times greater than the horizontal scenarios (Table 4). The subsequent collision risk estimate was 7.68 seals per year, which was 66.28% and 67.84% higher than that of the Band model and ERM, respectively (Table 4).

Table 4. Results from the SBA and those of the Band model and ERM taken from guidance note example, Falls of Warness [11]. Comparisons between model results are provided as percentage differences from the SBA horizontal approach. Note that ERM does not calculate collision probability.

Model	Result	Collision Probability	Collision Risk Estimate
SBA	Horizontal approach	0.3095	2.61 seals per year
	Vertical approach	0.9111	7.68 seals per year
	Difference: Horizontal vs. Vertical	66.03%	66.02%
Band	Worked Example	0.3077	2.59 seals per year
	Difference: SBA Horizontal	0.58%	0.77%
	Difference: SBA Vertical	66.23%	66.28%
ERM	Worked Example	-	2.47 seals per year
	Difference: SBA Horizontal	-	5.36%
	Difference: SBA Vertical	-	67.84%

4. Discussion

This work provides a quantitative comparison of the SBA model with the Band model and ERM, using the Falls of Warness results from the guidance note [11] as an example. When input parameters across the three models were the same, the difference in the results between the SBA model was <1% and <6% compared to the Band model and ERM, respectively. Therefore, these comparable results across the three different modeling approaches should give confidence to users and regulators that the SBA is a suitable alternative method for assessing collision risk, given that the Band models and ERM are quantitative methods commonly used and accepted in EIAs [3,4]. This is an important step both in providing this comparison and in providing the first worked example of how the SBA can be used to produce collision risk estimates that could be used within an EIA.

The SBA produced results closer to the Band model than ERM. This is likely due to the horizontal angle of approach, which is the same as used in the Band model, whereas the ERM calculates collision risk equally from all angles [11]. None of these methods are likely to be realistic, as animal behavior is likely to vary between and within species, with factors such as geographic location, bathymetric parameters, and flow speeds being influential. For example, a study of black guillemots (*Cepphus grylle*) tagged with depth loggers in the Pentland Firth [6] showed that 88% of dives were to the seafloor; therefore, the birds would likely have dived on a trajectory close to vertical. In the Falls of Warness example, considering a vertical angle of approach for harbor seals using the SBA, the collision risk estimate was three times higher than that of the SBA using a horizontal angle of approach, the Band model, and the ERM. Therefore, ecologically plausible deviations from the ERM and Band model assumptions can produce considerably different collision risk estimates, which demonstrates a critical limitation of using these traditional approaches to estimating collision risk, particularly when empirical data show that assumptions made in these models are limiting and do not capture the ecology and/or behavior of the species modeled [6,26–28]. Specifically, in moving away from the constraints of the Band model and ERM, to incorporate additional information on the angle of approach, we increased the collision risk estimate as compared to the other models by approximately three-fold. Therefore, in this hypothetical example, collision risk is greatly underestimated when using the Band model and the ERM highlighting the importance of addressing such issues. Whilst these models have provided collision risk estimates for EIAs for HATTs and VATTs [3,11,13], the need for a more robust assessment grows with the desire to build out to arrays of devices and where devices are novel in design (i.e., not HATT or VATTs).

The advantages of the SBA (Table 5), such as altering input parameters (e.g., angle of approach) [21] and estimating mortality [22], allow for more refined collision risk estimates that can better quantify uncertainties relating to key knowledge gaps, such as animal behavior when near the TEC(s). These can be incorporated in a flexible and transparent manner as requested by regulators, which would provide a more comprehensive assessment that can aid the decision-making process. For example, Horne et al. [22] demonstrated the application of a threshold approach to estimating mortality, whereby mortality was considered to occur above a certain speed of collision. That threshold could be increased (more precautionary) or decreased (less precautionary) as required and presented in a transparent fashion, as the speed of all collisions can be extracted from the SBA model [22]. With simulations taking days to run, the computational requirements of the SBA may be a factor in deciding if its use is required. For example, in cases where the Band model or ERM may be deemed sufficient by the regulator in areas where few animals occur, the size and/or number of devices pose negligible risk, and/or where mitigation measures, such as shutdown protocols and operation during daytime, will be in place.

Table 5. Characteristics in reference to the potential advantages and limitations of the three collision risk models.

Characteristic	Band	ERM	SBA
Model type	Formulaic	Formulaic	Simulations
TEC designs	HATT	HATT/VATT	Any
Angle of approach	Horizontal	All angles equally	Any angle set
Output	Single value	Single value	Flexible
Computational demand	Low	Low	High
Flexibility	Low	Low	High

Gathering more ecological data to refine collision risk estimates based on what we know or assume about the species' ecology and behavior has always been seen as key in progressing our understanding of collision risk. Whilst this is inevitably true, the advances in technology for addressing these uncertainties and knowledge gaps have accelerated at a far greater pace, as compared to those made in collision risk modelling. Where significant investment has been made to understand collision risk at many TEC sites, with site-specific surveys (e.g., [18,26,27]), the ability to incorporate this information into the traditional Band model and ERM is limited at best. Consequently, these data are arguably not refining collision risk estimates beyond adjusting local density values. Furthermore, obtaining behavioral data often comes at a significant cost to the developer at all stages of the project, for example, the cost of telemetry tags for tracking seals, the logistics of tagging the animals, and the analysis and reporting of the data require a significant budget. There are also ethical considerations with respect to capturing and handling animals and the need to ensure that the data collected are robust and fit for purpose and that their value is maximized such that they are as informative as possible with respect to assessing collision risk. Therefore, consideration needs to be given to the value of these data and how they are to be incorporated into the assessment to reduce uncertainty and to refine and improve collision risk probabilities prior to requesting those from an industry in its infancy, to spend significant resources on studies that may not, without the appropriate analytical tools available, reduce knowledge gaps and/or uncertainty.

In this regard, studies are beginning to gather more comprehensive information on animal behavior around devices, such as their fine-scale movement [26], response to the noise of the device [28], and movement in relation to the tidal flow in the area [7,27]. However, it is important to note the site-specific nature of these data [7,27] and that extrapolation to other locations should be performed with caution and the caveats of doing so should be explicitly outlined. As demonstrated here with the angle of approach, there are limitations to incorporating additional parameters into the Band model and ERM, whereas this is straightforward for the SBA. Consequently, as the SBA allows a range of input parameters and scenarios to be modeled [21], this provides the opportunity to assess ranges within parameters (e.g., swim speeds, animal size and shape, and dive profiles) to calculate collision risk and mortality estimates [22], which is often not possible, or at best, limited, when using the Band model or ERM. Furthermore, understanding to what extent parameters influence collision risk estimates is little understood, and by assessing a range of inputs, SBA model outputs could be gathered and used to better inform empirical data collection. Specifically, parameters that have the greatest influence on the estimates would be a primary focus with respect to gathering empirical data, if feasible.

Key factors often used as scalars on the collision risk model estimate are evasion and avoidance, which are extremely important parameters when assessing collision risk [5]. Where evasion is defined as a change in behavior to escape impact or contact with an MRE device at close range and avoidance is defined as animals moving away from the area around the device, at some distance from the object, these parameters are often incorporated qualitatively [3,13]. For example, 90% evasion/avoidance rates are typically used in assessments of collision risk [3]. These factors are the focus of recent studies [26,27] aiming to address these critical knowledge gaps. This research will be key to better informing evasion/avoidance rates, for example, by inclusion in calculations of animal density [27]. However, further work on how best to incorporate the findings from such studies on behavior around TECs into CRMs will also be important for reducing the uncertainties inherent in collision risk estimates produced when making assumptions on evasion/avoidance rates.

As empirical data improve and EIAs of array-scale projects and/or novel device types (i.e., not HATTs or VATTs) are required, the need for a more flexible and robust collision risk model becomes apparent. Using the methods mentioned above, the SBA can produce conservative estimates (i.e., using a precautionary approach) by implementing thresholds, if desired, to give a range of values in the absence of site-specific data. Parameters used can be taken from the literature and/or expert elicitation, which can be refined if site-specific data become available, or when changes in guidance from the regulator and/or their statutory advisors are issued. Given that uncertainty around collision risk estimates is a long-standing major barrier to the consenting of TECs, particularly o for arrays of devices [5], we need to find a way to progress in this industry. The SBA was developed to provide an alternative collision risk model that addresses several of the limitations of currently used collision risk models. The SBA has now been verified against the two CRMs traditionally used in EIAs and, where results were comparable across the same scenario, one simple but potentially ecologically important parameter was changed to demonstrate that, under a scenario where the animal approaches the device vertically, the Band model and ERM considerably underestimated the collision risk.

The SBA can be computationally time-consuming and requires more information. It may be that in some cases, where the risk is perceived as low, the Band model and/or ERM is proportionate and can be used in EIAs for single or small arrays of HATTs or VATTs in less sensitive areas (e.g., not near protected sites designated for marine mammals and seabirds). However, the introduction of the SBA into the collision risk modeling toolbox provides an option for a more robust, transparent approach that can quantify the impact of novel device designs [20] and provide more detailed outputs [22]. This now provides options for developers and their consultants to discuss which is the most suitable approach to assess collision risk in consultation with the regulator and other key stakeholders during the scoping phase of projects. And, where the SBA is preferred, parameters, their ranges, and any thresholds (e.g., for mortality) can also be discussed and agreed upon by stakeholders at this stage.

By advancing collision risk modeling for TECs to tackle one of the most long-standing and major barriers to progression for this industry, the SBA can assist in sustainable development, leading to more devices and array-scale projects consented which, in turn, will contribute to global renewable energy production and achieving net zero targets.

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