



Development and application of an environmental risk register for marine energy device and project developers

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ABSTRACT

The marine energy industry is steadily advancing as more devices are deployed worldwide. However, several challenges and barriers remain, such as lingering uncertainty regarding the potential environmental effects of marine energy devices on marine animals, habitats, and ecosystems. Concerns have led to difficulty navigating permitting and consenting processes and receiving authorization to deploy devices in the marine environment, including extended timelines and costs. Based on existing risk registers, a novel marine energy environmental risk register was created to help the marine energy industry move beyond these barriers. This risk register aims to aid marine energy device and project developers identify and assess potential environmental risks early in device design or project planning, document and track potential environmental interactions, prioritize risks and determine risk responses, and make decisions throughout device or project development. It can also be used as a tool to assist in communicating with regulators and advisors during permitting processes and to inform stakeholder and community engagement efforts. This paper details the methods and process to develop a risk register specific to environmental effects of marine energy and describes two use cases (one for wave energy and another for tidal energy) to highlight example results. Due to the tool's novelty, the paper showcases its application for the marine energy industry and acknowledges limitations and possible future improvements. Overall, the environmental risk register shows promise to support marine energy developers when identifying, tracking, and addressing potential environmental risks and to help successfully navigate permitting and deploy marine energy devices responsibly.

1. Introduction

While marine energy (energy from waves, tides, currents, and salinity and thermal gradients) is growing worldwide, albeit slowly, several challenges and barriers to progress remain. One of these is understanding the potential interactions between marine energy devices and marine animals, habitats, and ecosystems (Garavelli et al., 2024a). Whether due to remaining uncertainty, perceived effects, or actual risks, it can be difficult for developers to receive consent for ocean deployments of marine energy devices from the agencies responsible for managing ocean areas or resources (Barr et al., 2021; Kramer et al., 2020). Barriers to deployment resulting from uncertainties around environmental effects is a risk for the advancing industry, in some cases leading to untimely and costly permitting/consenting processes (Freeman et al., 2022). Improving current understanding and gaining

consensus from subject matter experts on environmental effects can help inform permitting processes and aid discussions with regulators and stakeholders, including local communities, to address concerns (Garavelli et al., 2024a; Copping and Hemery, 2020).

Typically, environmental assessments are carried out while project planning either during or after site selection. However, there is also an opportunity to assess potential environmental effects earlier, during technology development and device design. Accounting for possible environmental effects at these earlier stages can help marine energy technology or device developers consider how their devices might interact with the marine environment and make design decisions that can potentially lessen or avoid environmental effects and/or costly changes to device design at a later stage (Hodges et al., 2023). Such decisions will need to be in line with engineering and technical feasibility for device success, but equipping device developers with this

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information allows for a more holistic approach to decision-making. Assessing environmental interactions earlier can also help marine energy project developers detail potential effects to aid discussions with regulators and stakeholders and inform permitting processes and project management, such as monitoring and research needs. This is especially pertinent because many marine energy technologies are still being developed, are testing in open-ocean environments for the first time, or are at the beginning of larger project planning discussions for long-term deployments (Ocean Energy Systems, 2023a; Ocean Energy Systems, 2023b; PRIMRE, 2024).

One method of assessing the potential risks of a device or project is through risk registers. Risk registers are used by various industries (e.g., construction, health, ecology, engineering) to make informed decisions as they document possible risks, identify the level of risk, and help detail response plans (Kuchta and Ptasińska, 2017; Latham et al., 2017; Mansfield et al., 2015; Rees et al., 2022). Engineering risk registers are one commonly used example, including within the marine energy industry. In particular, the United States Department of Energy and the National Renewable Energy Laboratory have developed a marine energy risk management framework and accompanying engineering risk register that have been used in the United States (Snowberg et al., 2024; Snowberg and Weber, 2015). While some of these may touch on environmental risks, they are typically focused on engineering components and human health and safety and do not include the intricacies of how a marine energy system may interact with the marine environment in a way that is meaningful for permitting and licensing assessments. In general, there are limited examples of risk registers for environmental-specific applications (e.g. (Rees et al., 2022; Mace et al., 2015),) and no environmental risk register available for the marine energy industry. This work focused on developing a marine energy-specific environmental risk register.

In a nascent industry, such as marine energy, where there is limited data and information available on potential environmental effects from ocean deployments, qualitative risk assessments can be employed (FAO/WHO, 2009). A qualitative risk register and its associated risk matrix can be easy to use (Ristic, 2013), document potential areas of concern, inform decision-making, help set priorities, and identify research needs (Rees et al., 2022; Coleman and Marks, 1999; Hashim et al., 2021). In order for qualitative risk assessments to be effective, they need to be clear and specific in their methods, use, audience, definitions, and limitations (Rees et al., 2022; Ristic, 2013). This paper describes a novel, qualitative environmental risk register (ERR) that can be used by marine energy technology/device developers and project developers to document, examine, and organize potential environmental risks for marine energy deployments and to recommend strategies to address them.

The ERR can also be used to track environmental risks throughout the lifetime of a project and can be employed at various stages from device design through the environmental monitoring of deployed devices. This paper details the development and use of the ERR for the marine energy industry so that device and project developers can easily apply this tool for their needs. The following sections describe the methods used to develop the ERR, including definitions and limitations, and describes its application through use cases for wave and tidal energy devices. The paper ends by highlighting areas for future development.

2. Methods

2.1. Developing the environmental risk register

In creating the ERR, the aim was to make a tool that could incorporate detailed documentation of environmental risks while remaining simple and easy to navigate. ERR development began with a literature review of available risk registers, including Snowberg and Weber (2015) (the 2015 version was used as the 2024 update, Snowberg et al. (2024), was not released until after the ERR was developed) and in particular,

environmental risk registers. Because the ERR is specific to both environmental effects and marine energy, no one risk register had all the necessary elements. Therefore, the ERR incorporated elements from several relevant risk registers and other resources across a range of industries including marine energy (Snowberg and Weber, 2015), transportation (Minnesota Department of Transportation, 2024), natural capital assets (Rees et al., 2022; Mace et al., 2015), offshore wind (Latham et al., 2017), and alternative energy development (MMS, 2007). The result was an ERR template (available in supplementary materials, Appendix A) that can be completed by marine energy device or project developers with environmental expertise or by a third party providing expert evaluation of environmental risks. Ideally this is an expert, or team of experts, who has studied environmental effects of marine energy and has specific knowledge about these interactions and experience working in this field or an analogous marine industry. This is likely a consultant, someone with maritime or in-water project permitting experience, or a subject matter expert from a university or research laboratory.

A key component of the ERR is the risk assessment. To define environmental risks, common industry terms were used (e.g., “stressors” and “receptors”) to characterize potential environmental interactions (Tethys, 2024). To assess a particular environmental risk, a probability and impact matrix (also known as a risk matrix) was used following a similar approach to Snowberg and Weber (2015). Both the likelihood of occurrence and potential impact of the environmental interaction were used and defined in the ERR (Table 1). Likelihood in the ERR can be designated as low, medium, or high; impact can be designated as negligible, minor, moderate, or high. Likelihood-level definitions were based on Snowberg and Weber (2015), which are commonly used in risk registers, and impact-level definitions were based on those defined by the U.S. Bureau of Ocean Energy Management to assess the potential impacts of alternative energy development on biological and physical resources (MMS, 2007). Unlike other risk registers and their associated matrices, quantitative descriptions were not used for likelihood levels. Understanding on environmental effects of marine energy is still being developed and uncertainty remains (Garavelli et al., 2024a; Copping and Hemery, 2020), making it challenging to assign quantitative values that are meaningful or accurate across a spectrum of potential device-environment scenarios. While the ERR and the associated

Table 1

Definitions for likelihood and impact designations within the ERR, based on those used by the U.S. Bureau of Ocean Energy Management (MMS, 2007) and Snowberg and Weber (2015). Each designation was assigned a value for use in the risk matrix.

	Definition	Value
Likelihood	The probability of an environmental interaction occurring.	
	Low Low likelihood of the interaction occurring.	1
	Medium Medium likelihood of the interaction occurring.	2
	High High likelihood of the interaction occurring.	3
Impact	The estimated degree of effect from the interaction.	
	Negligible No measurable impacts.	1
	Minor Most impacts to the affected receptor could be avoided with proper mitigation. If impacts occur, the affected receptor will likely recover without any mitigation once the impacting agent is eliminated.	2
	Moderate The viability of the affected receptor is not likely to be threatened although some impacts may be irreversible, or the affected receptor is likely to recover completely if proper mitigation is applied during the life of the project or proper remedial action is taken once the impacting agent is eliminated.	3
	High Impacts to the affected receptor are unavoidable. The viability of the affected receptor may be threatened, and the affected receptor is not likely to fully recover even if proper mitigation is applied during the life of the project or remedial action is taken once the impacting agent is eliminated.	4

probability and impact matrix was developed as a qualitative assessment to help developers prioritize risks, values were assigned to each likelihood and impact designation to calculate the risk priority number (RPN).

For each potential risk, the values of the likelihood and impact levels can be multiplied together to calculate the RPN. RPNs range from 1 (low) to 12 (high) and can be applied to the risk matrix to equate potential risks with a low, medium, or high priority (Fig. 1). The RPN may be influenced by the impact level, likelihood level, or both. Due to the inherent challenge in quantifying environmental risks, the RPN does not denote the risk itself, but rather the priority in which device or project developers may want to address the various risks. Prioritizing risks using RPNs and the risk matrix aids developers throughout device design and/or project planning processes by providing a relative assessment of risk and associated likelihood and impact for a particular environmental interaction.

Throughout the ERR, references with information on environmental interactions were included to give users the ability to easily access key documents and other resources that might be useful throughout device design, project planning, and development. To inform risk assessments and using the best available science, Copping et al. (Copping and Hemery, 2020) and Garavelli et al. (2024a) were included, which provide comprehensive assessments of the state of the science regarding environmental effects from marine energy. Key references from other sectors that are relevant for the marine energy industry (e.g. (Love et al., 2016),) were also incorporated. In addition, the ERR includes references for the OES-Environmental guidance documents¹ on key environmental interactions (OES-Environmental, 2024) that provide summaries of current knowledge for each interaction and link to additional information and data that can be used to understand environmental effects from marine energy. The ERR also included space to identify which agency serves as the lead for permitting and/or regulating specific environmental concerns, and who developers are likely to communicate with.

2.2. Defining the environmental risk register sections

The ERR has three main sections—device component, environmental

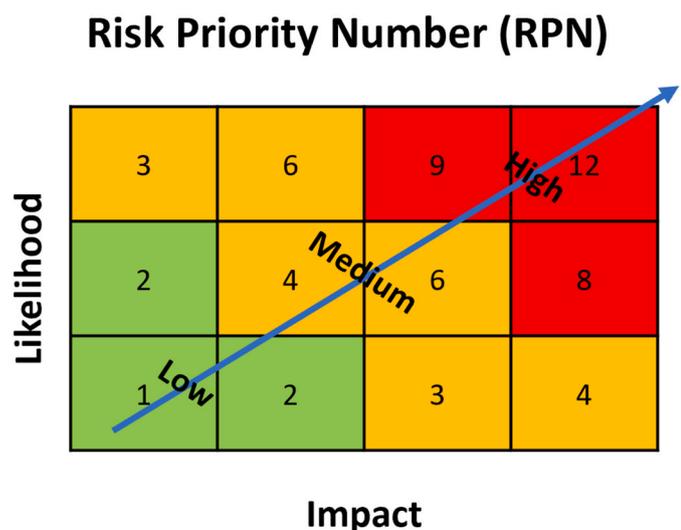


Fig. 1. Risk matrix showing the RPNs for the ERR, based on methods in Snowberg and Weber (Snowberg and Weber, 2015). RPNs are calculated by multiplying the assigned likelihood and impact values of an environmental interaction.

risk, and risk response—as shown by the conceptual framework developed to help define the ERR (Fig. 2).

2.2.1. Device components

The ERR was organized around the components of a marine energy system including the device and associated infrastructure, such as anchors, mooring lines, and cables. Device subcomponents, such as the internal mechanisms within the device, that do not directly interact with the environment were not considered. For instance, underwater noise from devices generally comes from the power take-off, which is sufficient for identifying and assessing risk and does not require identification of the internal components that make up the power take-off. Clarifying the level of detail and that the ERR should be focused on components that may directly interact with the environment helped keep the ERR detailed yet focused on elements that may be linked to environmental risk.

2.2.2. Environmental risk and assessing risk

The next section of the ERR identifies the environmental risks for each component and was organized by stressors and receptors. Stressors are aspects of a marine energy system that may cause stress (e.g., underwater noise from a device, habitat change from components on the seafloor, collision risk from tidal turbine blades), and receptors are the marine animals, habitats, and/or ecosystem processes that may be affected (e.g., marine mammals, fish, sediment transport) (Tethys, 2024; Boehlert and Gill, 2010). The specific stressors and receptors included in the ERR are those that are identified and defined within the literature and key industry references (Copping and Hemery, 2020; Tethys, 2024; Garavelli et al., 2024b). For each device component and associated stressors and receptors, descriptions were included to clearly specify each environmental, or stressor-receptor, interaction and aid communication and common understanding.

When assessing risks within the ERR, it was intended that impacts to animals are assessed based on the population rather than the individual, in line with the U.S. Bureau of Ocean Energy Management's definitions (MMS, 2007). This also applies for effects to habitats, where impact should be assessed based on the overall impact to that habitat type. For example, risk of entanglement to marine animals should be assessed based on the population-level impact to the marine mammal species, not an individual animal. The ERR uses general categories for receptors (such as “marine mammals,” “fish,” “invertebrates,” etc.) to keep the ERR concise and avoid redundancy. However, if a species of concern (e.g., endangered, threatened) is expected to be present at a deployment location, the impact to an individual may in fact affect the population. In these cases, an additional row could be incorporated for the potential risk to that specific species or population (e.g., Southern Resident killer whale [*Orcinus orca*], North Atlantic right whale [*Eubalaena glacialis*]), particularly when impact may differ for a species of concern versus the general receptor category used.

2.2.3. Risk response

The last section of the ERR documents the risk response for each environmental interaction. This section was organized around developing a strategy to address or accept potential risks. The strategies used in the ERR were adapted from other risk assessments or risk registers (Snowberg and Weber, 2015; Minnesota Department of Transportation, 2024) and include avoid, transfer, mitigate, monitor, or accept (Table 2). While monitor does not appear to be a typical strategy included in risk registers, it was included in the ERR as it is a common method to manage potential environmental risk, particularly in the face

¹ <https://tethys.pnnl.gov/guidance-documents>.

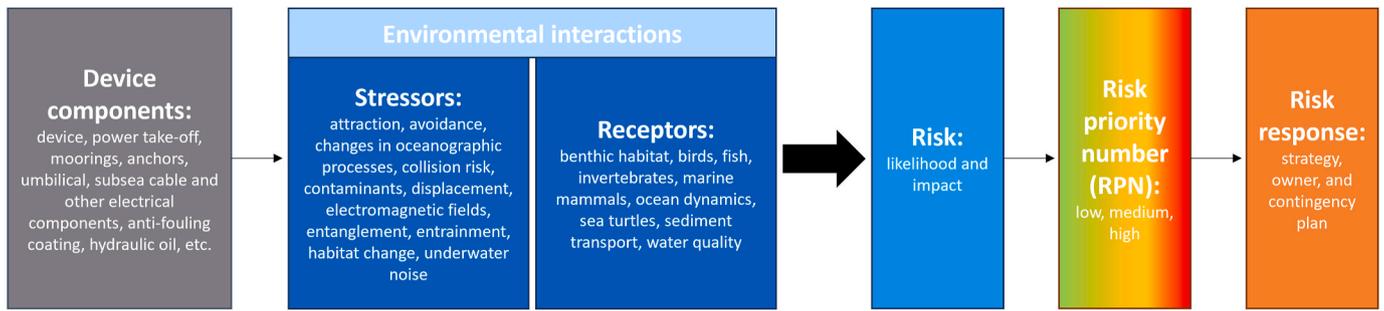


Fig. 2. Conceptual framework for the ERR.

Table 2

Strategies within the risk response section of the ERR. Definitions for avoid, transfer, mitigate, and accept are from Snowberg and Weber (2015).

Strategy	Definition
Avoid	Ensuring the risk cannot occur or will have no impact on the project.
Transfer	Transferring the risk to a third party (e.g., insurance company or via contracts or outsourcing).
Mitigate	Reducing the probability and/or consequence of a risk.
Monitor	Monitoring the risk during project operations.
Accept	Accepting the risk without pursuing any of the other strategies.

of uncertainty (e.g., adaptive management²) (Eaves et al., 2022; Freeman et al., 2024; Le Lièvre et al., 2020). If needed, a contingency plan to enact if any unacceptable risk still occurs, can be described. For each strategy, a risk owner can be assigned. The risk owner will be the responsible person or party for carrying out the risk response and contingency plan and updating that risk within the risk register as needed.

2.3. Review of the environmental risk register

The ERR was initially developed to support wave energy device developers and help them better understand potential environmental risks associated with their specific technologies. The ERR has since been used to also support marine energy project developers to document potential environmental risks for planning deployments. As a part of these efforts, the ERR and associated risk assessment were reviewed by device and project developers through iterative feedback processes that refined the ERR and its application. Additionally, experts on environmental effects of marine energy also reviewed the ERR to refine the risk assessment.

2.4. Use cases development

Because of the proprietary nature of marine energy device and project design and associated information, the ERR is applied to two generic use cases (one for wave energy and one for tidal energy) in this paper to provide examples. Generic marine energy devices informed by systems currently found in the marine energy industry were used as proxies for the use cases to highlight common environmental interactions for wave and tidal energy devices. The figures presented in the use cases were created to be an illustrative aid for understanding the ERR and its associated example risk assessments. While deployment location is an important aspect of the ERR and risk assessment, the use cases are presented as generic examples and therefore do not have specified locations. When using the ERR, location-specific information

² Adaptive management is an iterative approach, often called “learn by doing”, where projects with scientific uncertainty are managed by monitoring and data collection that inform decisions overtime. This provides a pathway forward for projects with uncertainty, while also decreasing scientific uncertainty and increasing knowledge from monitoring data (Le Lièvre et al., 2020).

should be included in the risk assessment, mainly by identifying the species and habitats present at a deployment location and assessing the environmental interaction based on these factors. The focus of this paper is on the presentation of the ERR as a tool and how to employ it, rather than how to carry out the environmental risk assessment, therefore for simplification these specifics are not included.

The example risk assessments presented in the use cases are based on the best available information, as noted in Section 2.1, and are only provided as an example to aid future use of the ERR. This publication is focused on the ERR and its application, rather than the current state of understanding to assign likelihood and impact to each environmental interaction. When using the ERR, the risk assessment and designation of likelihood and impact should be carried out by experts on environmental effects of marine energy using the best available data and information (e.g. (Garavelli et al., 2024a; Copping and Hemery, 2020)).

For the risk response, some examples were developed to show how this section of the ERR can be used, but the risk responses will be specific to each developer and will also likely be based on permit requirements. For the wave energy use case, the PacWave South test site off the coast of Newport, Oregon was used to provide examples of risk responses as they have documented approaches to addressing potential environmental effects within their Client Handbook (Oregon State University, 2024) and Protection, Mitigation, and Enhancement Measures (Oregon State University, 2019).

3. Applying the ERR through use cases

As described by Snowberg et al. (2024), the process for risk assessment entails identifying risks, analyzing risks, planning and executing risk responses, and monitoring and controlling risks. The following sections provide hypothetical examples of ERR application through two generic use cases, highlighting aspects of the risk assessment and risk response to show how this approach can be implemented.

3.1. Wave energy use case

For the wave energy use case, a generic point absorber wave energy device (Fig. 3) was assessed. The full ERR for the wave energy use case can be found as supplementary materials (Appendix B). Some example results and findings are highlighted below.

Eight different device components were identified: the three gravity anchors and associated mooring lines, the internal power take-off system, the device itself (floating body), the umbilical, the subsea power cable and other electrical elements such as the substation, the anti-fouling coating, and the internal hydraulic oil. Based on these components, nine potential stressors were identified—changes in habitats, entanglement, underwater noise, attraction, avoidance, displacement, changes in oceanographic systems, electromagnetic fields, and contaminants. Nine possible general categories of receptors were also identified—benthic habitats, fish, invertebrates, marine mammals, sea turtles, birds, ocean dynamics, sediment transport, and water quality. Using the current knowledge base and understanding of these stressor-

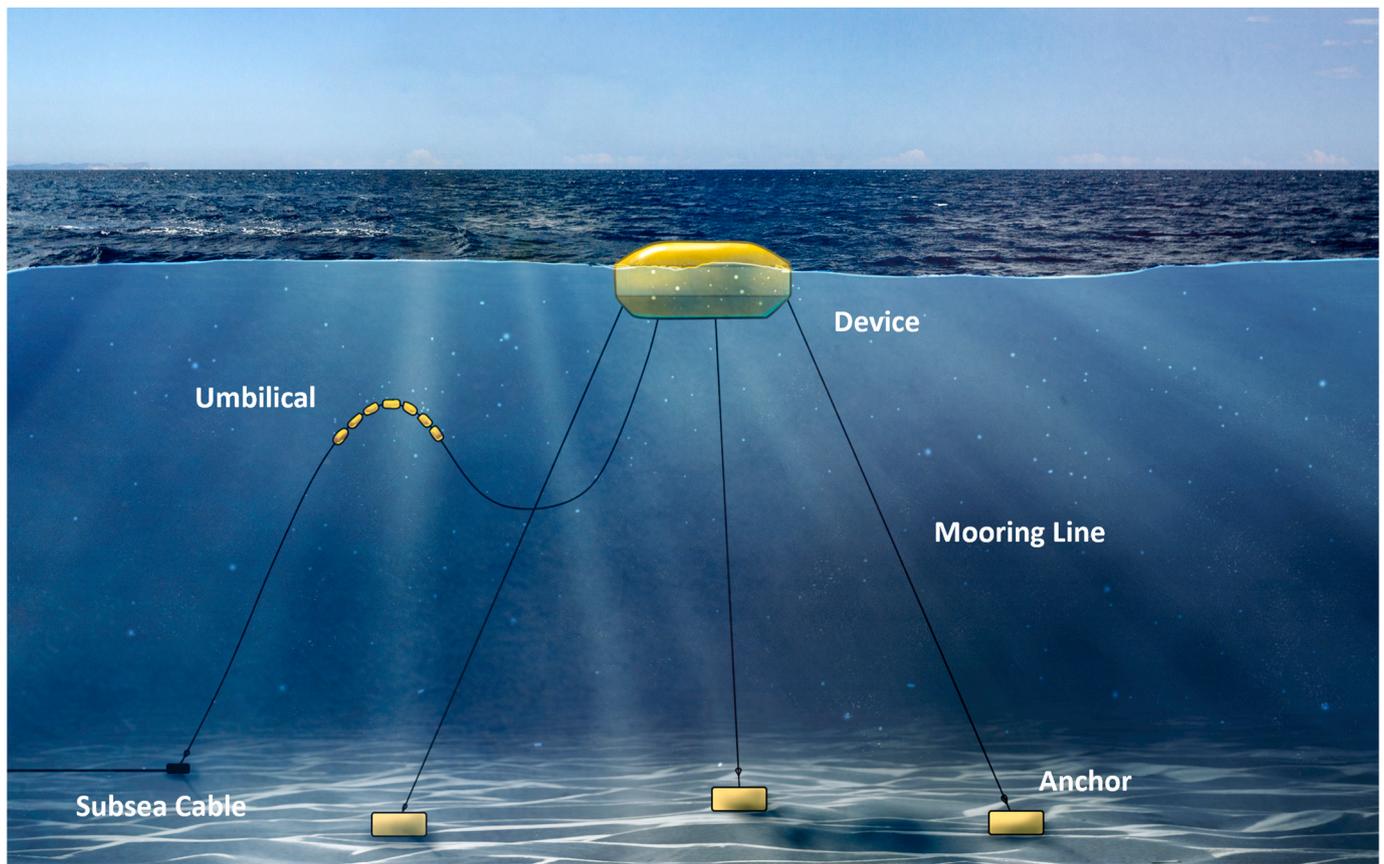


Fig. 3. Illustration of a wave energy device (point absorber) to show the various device components of the generic marine energy system (device, mooring lines, anchors, umbilical, and subsea power cable) and identify potential environmental risks. Illustration by Stephanie King, Pacific Northwest National Laboratory.

receptor interactions, each were assigned a likelihood and impact level and RPNs were calculated.

There were 48 potential environmental interactions identified for the wave energy ERR example, with likelihood ranging from low to high and impact ranging from negligible to moderate. Thirty-six were designated as low likelihood, including potential risks such as mooring line entanglement on all receptors; avoidance, displacement, and changes in oceanographic systems from the device on all receptors; and electromagnetic fields from the umbilical, the subsea power cable, and other electrical infrastructure on all receptors. Two potential environmental interactions were designated as high likelihood: (1) changes in benthic

habitats from the addition of the three gravity anchors, and (2) changes in benthic habitats from the addition of subsea power cable and other electrical infrastructure. These potential risks have a high likelihood of occurring because placing any new infrastructure on the benthos will result in changes (Garavelli et al., 2024b; Hemery et al., 2020). Fifteen potential risks were marked as having negligible impact, which included attraction, avoidance, displacement, and changes in oceanographic systems on all receptors. There were no potential risks with high impact. Some risks were noted as having moderate impact, including secondary entanglement from the mooring lines for marine mammals, sea turtles, fish, and diving seabirds. Based on the likelihood and impact values, the

Table 3

A sample of ERR results from the wave energy use case. Additional details for each environmental interaction can be found in the supplementary materials (Appendix B).

Device					
Component	Stressor	Receptor	Likelihood	Impact	RPN
Gravity anchors	Habitat change	Benthic habitat	High	Minor	6
Gravity anchors	Habitat change	Fish	Medium	Minor	4
Mooring lines	Entanglement	Marine mammals	Low	Minor	2
Mooring lines	Entanglement (secondary)	Marine mammals	Low	Moderate	3
Power take-off	Noise	Marine mammals	Low	Moderate	3
Power take-off	Noise	Fish	Low	Moderate	3
Device	Attraction	Marine mammals	Medium	Negligible	2
Device	Avoidance	Marine mammals	Low	Negligible	1
Device	Displacement	Marine mammals	Low	Negligible	1
Device	Changes in oceanographic processes	Ocean dynamics	Low	Negligible	1

RPNs for all environmental interactions ranged from one (green) to six (yellow) (Table 3). The lowest RPNs included interactions such as avoidance and displacement of marine mammals, sea birds, fish, and sea turtles and changes in oceanographic systems that affect ocean dynamics and sediment transport. For all these environmental interactions, likelihood was designated as low (1) and impact as negligible (1), making the RPNs one (Garavelli et al., 2024b; Hemery et al., 2024). The highest RPNs were for changes in benthic habitat from the installation of device anchors and electrical infrastructure; due to a high likelihood (3) and minor impact (2) the RPNs were six (Garavelli et al., 2024b; Hemery et al., 2020).

For the wave energy use case, example risk responses from the PacWave South test site were included in the ERR. For example, the PacWave South Client Handbook describes PacWave's responsibility for implementing monitoring plans for changes in benthic habitat (Oregon State University, 2024), so PacWave was designated as the risk owner for all risks related to habitat change with the strategy being designated as “monitor.” Alternatively, PacWave requires that “[device developers] must design and maintain cables and moorings in configurations that minimize the potential for marine mammals or sea turtle entrapment or entanglement (e.g., cable and lines should remain under tension) to the extent practicable” (Oregon State University, 2024). PacWave's Protection, Mitigation, and Enhancement Measures also note that “PacWave is responsible for implementing mitigation for marine species entanglement” (Oregon State University, 2019). In this case, for all potential risks related to entanglement the risk owner was noted as both the device developer and PacWave. Regarding contingency plans, one example from PacWave South is for underwater noise. The risk response was marked as monitor because PacWave is responsible for implementing its acoustics monitoring plan (Oregon State University, 2024). Moreover, “[device developers] will be required to take additional measures to

minimize and mitigate for sound if [wave energy devices] and their mooring systems produce sound in excess of the [National Marine Fisheries Service]'s published harassment threshold(s)” (Oregon State University, 2024).

3.2. Tidal energy use case

For the tidal energy use case, a horizontal axis tidal turbine (Fig. 4) was assessed. The full ERR for the tidal energy use case can be found as supplementary materials (Appendix C). Some example results and findings are highlighted below.

Seven different device components were identified: the three-point gravity base, the internal power take-off system, the device itself, the turbine blades, the subsea power cable and other electrical elements such as the substation, the anti-fouling coating, and the internal hydraulic oil. Based on these components, nine potential stressors were identified—changes in habitats, underwater noise, collision risk, attraction, avoidance, displacement, changes in oceanographic systems, electromagnetic fields, and contaminants. Eight possible general categories of receptors were also identified—benthic habitat, fish, invertebrates, marine mammals, birds, ocean dynamics, sediment transport, and water quality. Using the current knowledge base and understanding of these stressor-receptor interactions, each were assigned a likelihood and impact level and RPNs were calculated.

There were 29 potential environmental interactions identified for the tidal energy ERR example, with likelihood ranging from low to high and impact ranging from negligible to moderate. Nineteen environmental interactions were designated as low likelihood including, underwater noise affecting marine mammals and fish; collision risk to marine mammals, fish, and diving seabirds; avoidance, displacement, and changes in oceanographic systems from the device on all receptors; and

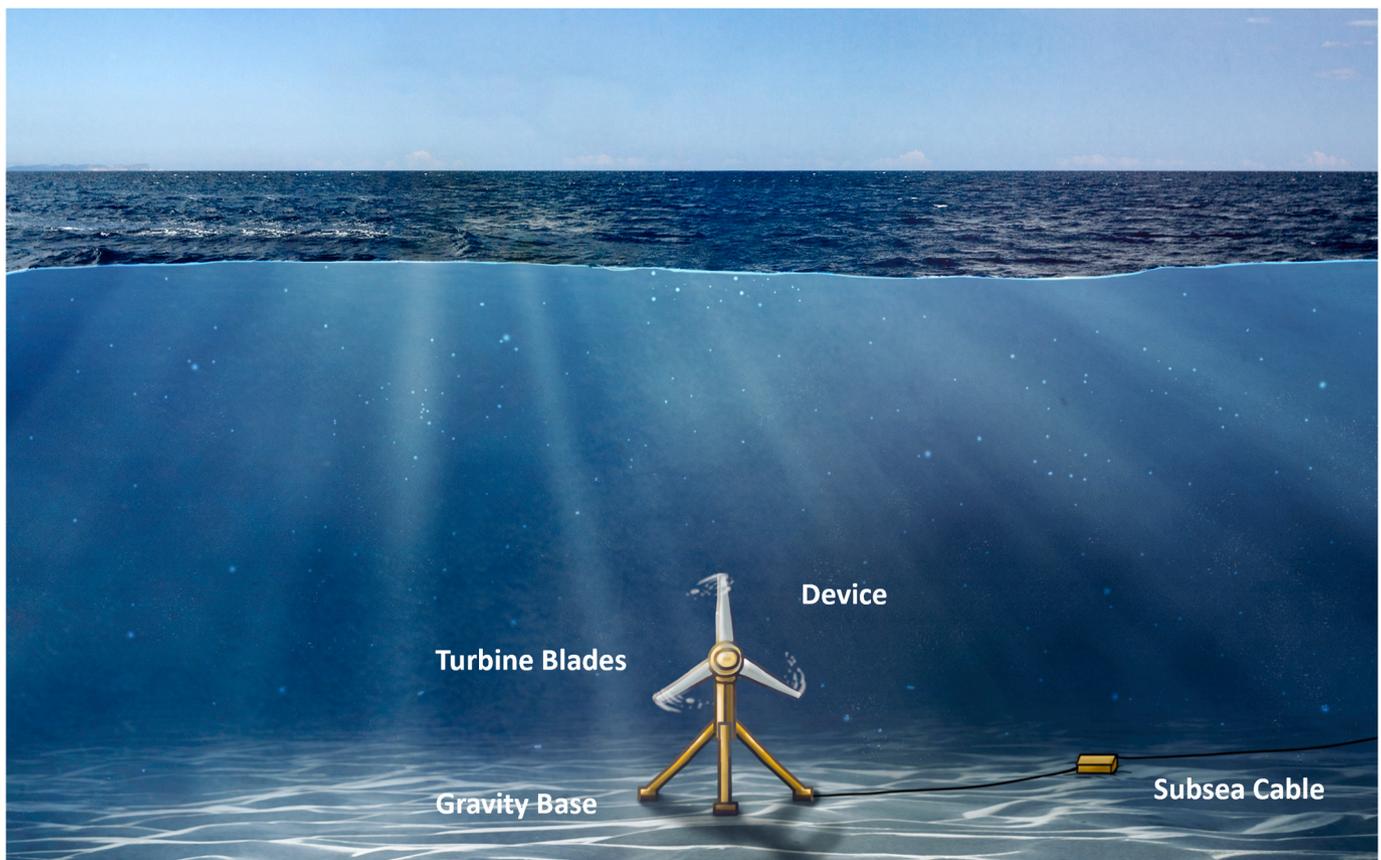


Fig. 4. Illustration of a tidal energy device (axial flow turbine) to show the various device components of the generic marine energy system (e.g., turbine blades, subsea power cable, gravity base) and identify potential environmental risks. Illustration by Stephanie King, Pacific Northwest National Laboratory.

electromagnetic fields from the subsea power cable and other electrical infrastructure on all receptors. As with the wave energy use case, two potential risks were designated as high likelihood: (1) changes in benthic habitat from the addition of the three-point gravity base, and (2) changes in benthic habitat from the addition of the subsea power cable and other electrical infrastructure. These are marked as such because placing any new infrastructure on the benthos will result in changes (Garavelli et al., 2024b; Hemery et al., 2020). Fourteen potential risks were noted as having negligible impact, including attraction, avoidance, displacement, and changes in oceanographic systems on all receptors. There were no potential risks with high impact, and the only risk designated as having moderate impact was collision risk to marine mammals, fish, and diving seabirds. Based on the likelihood and impact values, the RPNs for all environmental interactions ranged from one (green) to six (yellow) (Table 4). The highest RPNs were for changes in benthic habitat from the foundation and electrical infrastructure. Based on the high likelihood (3) and minor impact (2) the RPNs were six (Garavelli et al., 2024b; Hemery et al., 2020). The lowest RPNs included interactions such as avoidance and displacement of marine mammals, diving seabirds, fish, and invertebrates and changes in oceanographic systems that affect ocean dynamics and sediment transport. For all these interactions, likelihood was designated as low (1) and impact as negligible (1), making the RPNs one (Garavelli et al., 2024b; Hemery et al., 2024).

4. Discussion

4.1. Using the ERR to aid the marine energy industry

The goal of the ERR is to support marine energy device and project developers by providing a standard method to identify, document, track, and assess environmental risks based on general regulatory criteria and to offer a tailored assessment based on the marine energy device and deployment location. The methods describe the development of the ERR and detail each section of the ERR. The use cases provide examples of its application and highlight the value of the ERR to aid in environmental risk assessments for the marine energy industry. For instance, the likelihood and impact evaluations and associated RPNs can support device or project developers' decision-making throughout design and planning, particularly how to prioritize and address potential environmental interactions, such as those with higher RPNs. Doing so allows the ERR to facilitate detecting potential risks early in the device or project design process and address uncertainties to avoid challenges such as costly changes to a device at later stages and lengthy permitting.

The ERR can also help developers identify opportunities to lower the

likelihood or impact of a risk from specific device components or project decisions. Ideally, the ERR is used in parallel with the marine energy engineering risk register from Snowberg et al. (2024) during device design when developers have the most flexibility to alter different components based on identified environmental interactions. For example, with the wave energy use case, a developer could decide to change from using large gravity anchors to anchors with smaller footprints to reduce the potential risk from changes in habitat. In this case, the ERR can be revised based on the change in device components to reflect any potential likelihood or impact, and therefore RPN, shifts. However, it may not be possible to redesign or choose an alternative option, particularly when a component is integral to a device's function. In this case, identifying the risk and the appropriate response within the ERR can help both track and manage the risk early on. This is particularly important for stressors that require monitoring. One example is underwater noise from a device's power take-off. Not only is it unlikely that design decisions could fully remove this stressor and associated risk, but it is hard to quantify the level of noise emissions from a device until it is deployed. There is consensus that underwater noise from small numbers of marine energy devices is not a significant environmental concern based on measurements showing that, to date, devices typically do not surpass regulatory thresholds (Freeman et al., 2024; Copping et al., 2020). However, for devices that have not measured their noise output in the marine environment, it is important to track this risk and monitor it once the device is in the water. In these ways, the ERR can inform decision-making early in design, aid in tracking risks, and support the planning and execution of risk responses.

In addition, the ERR can serve as a resource for project planning and permitting processes, and ultimately for successful development of marine energy deployments. The results of the ERR can be communicated in a summarized manner with regulators during permitting discussions to help align risk management and responses with regulators' environmental mandates to comply with federal and/or state laws (e.g., Endangered Species Act). The ERR does not replace any regulatory guidance or required procedures for risk management such as spill plans, vessel transit requirements, or other environmental requirements. Therefore, decisions related to potential risks and associated responses will need to be made in conjunction with the relevant regulatory agencies, which is what the ERR is well suited for.

The ERR can also be used to support communicating information to stakeholders. Some examples of this include documenting potential environmental risks in a manner that is easy to communicate, particularly for developers and their teams to have consistent and easy to access information; conducting outreach and engagement with local communities to help understand environmental interactions and how a project

Table 4

A sample of ERR results from the tidal energy use case. Additional details for each environmental interaction can be found in the supplementary materials (Appendix C).

Device Component	Stressor	Receptor	Likelihood	Impact	RPN
Gravity base	Habitat change	Benthic habitat	High	Minor	6
Gravity base	Habitat change	Fish	Medium	Minor	4
Turbine blades	Collision	Marine mammals	Low	Moderate	3
Turbine blades	Collision	Fish	Low	Moderate	3
Power take-Off	Noise	Marine mammals	Low	Moderate	3
Power take-Off	Noise	Fish	Low	Moderate	3
Device	Attraction	Marine mammals	Medium	Negligible	2
Device	Avoidance	Marine mammals	Low	Negligible	1
Device	Displacement	Marine mammals	Low	Negligible	1
Device	Changes in oceanographic processes	Ocean dynamics	Low	Negligible	1

plans to assess or respond to each potential risk; or sharing device or project options with stakeholders to receive feedback on what is best suited for a particular area or community. For example, remote communities, particularly in areas where energy costs are high, may be good candidates for marine energy. A developer could go one step further and use the ERR to document potential risks voiced by these communities and stakeholders and offer involvement in decision-making and management, applying the ERR to aid device choice, site selection, and risk response. Low-carbon energy options may be appealing, but potential impacts on the local environment that might affect socially, culturally, or economically important resources (e.g., where fishing is integral to livelihoods in the community) may drive community concern. In these cases, the ERR can be used to help communicate with stakeholders.

Last, the ERR can provide additional value as a method for independent assessment of the level of environmental risk associated with a specific device or project. Using the ERR requires input from device or project developers, particularly on details such as device components and location, but otherwise can be completed by an independent entity. It is suggested that the environmental risk assessment is carried out by experts who are knowledgeable about potential environmental effects from marine energy, which provides an opportunity for an independent, third-party assessment. This is useful for both funding agencies and marine energy investment shareholders, as well as for communities who may perceive an independent assessment of environmental risk as a strength of a proposed device or project.

The ERR was developed for device and project developers in the marine energy industry. Using the ERR can also add value for regulators, stakeholders, and funders to build confidence in marine energy projects and the processes developers have gone through to assess, understand, and manage potential environmental risks. Taking an approach that can minimize risk to the extent practicable is evidence of good stewardship, particularly if the ERR risk assessment is carried out by a third party.

4.2. Limitations

There are several limitations within the ERR. As noted by [Snowberg et al. \(2024\)](#), it is inherently challenging to assign likelihood and impact values, including for environmental risk due to its subjective nature. This is particularly true for identifying environmental risks in a relatively new industry like marine energy. There is some scientific consensus on the level of risk around certain stressor-receptor interactions for small numbers of devices based on the existing marine energy knowledge base and evidence from analogous industries ([Freeman et al., 2024](#); [Copping et al., 2020](#)). However, only a small number of marine energy devices have been deployed around the world and available data to inform environmental interactions are limited, particularly for some risks such as collision risk. Risk registers can provide a starting point for evaluations and decision-making, which is particularly useful due to uncertainty around environmental effects of marine energy and the limited data available. As more data are collected from marine energy deployments and uncertainty decreases, the accuracy of the ERR and its associated risk assessment (i.e., likelihood and impact) will increase.

Further, because a risk's RPN may be influenced by its impact level, likelihood level, or both, it is important to consider the availability of data and information used to inform these designations. It may also be necessary to reevaluate the designations and risk assessments as new information on environmental effects of marine energy becomes available. Due to the current state of marine energy development, most data and information are available only for single devices or small numbers of devices. Therefore, the risk assessment in the ERR may be most accurate for smaller-scale deployments. As the marine energy industry scales up to larger, array-scale deployments, there may be more uncertainty when using the ERR due to the paucity of data ([Hasselman et al., 2023](#)). To apply the ERR for larger-scale developments, data and information from small-scale deployments will need to be used to inform risk assessments

and applied carefully until there are environmental data collected around large numbers of devices and validated models to inform scaling up. Once this knowledge is accumulated for large-scale marine energy developments and available to support comprehensive understanding on environmental effects, the ERR and its associated risk assessment will be more robust and uncertainty will decrease.

The ERR presented here does not include several considerations, particularly those present in [Snowberg et al. \(2024\)](#). The ERR was developed to assess the operational phase of marine energy developments. However, other project phases, most notably installation and decommissioning, will also have environmental interactions to consider. It can be challenging to incorporate and assess environmental risk for each phase, and this may be best suited for project developers who are creating plans for installation of marine energy systems and considering decommissioning options. Adding other phases may not be well suited for device developers who are early in device design. It should also be noted that while siting is an important aspect of project planning, the ERR is not a siting tool and is best applied at a determined project location or used to aid in decision-making by comparing environmental risks between already identified potential deployment locations.

There are various methods for risk assessments within risk registers. One in particular that may be considered and incorporated in the future comes from failure mode and effects analysis (FMEA) ([Bowles and Peláez, 1995](#)). FMEA risk assessments include detection, designating the level of detection capability necessary to observe or measure a particular risk ([Liu et al., 2013](#)). Detection is incorporated with likelihood and impact (known as occurrence and severity for FMEA) as part of evaluating the risk and RPN, which would then be calculated by multiplying the three values together. As more information becomes available on environmental interactions, detection may be a variable that could be estimated and incorporated into the ERR.

Additional aspects could also be added to future iterations of the ERR to support developers in tracking and managing risks, including timing and risk status. In [Snowberg et al. \(2024\)](#), timing is used to denote if a risk response is carried out as part of a schedule, and when the response should occur or if the response is only triggered by a certain condition. This could be useful for developers, especially in cases with higher risks and/or complex responses that need to be carried out based on regulatory schedules or triggers. Similarly, risk status is used to denote if a risk is actively present and being monitored, if it is not a high priority, or if it is no longer considered a risk and can be retired ([Minnesota Department of Transportation, 2024](#)).

Once the risk response has been implemented it may also be useful to incorporate an assessment of residual risk (the expected results from the risk response). This was considered during ERR development but was not included due to limited available data that make it challenging to assess the results of mitigation or monitoring measures undertaken. However, this could be applied on a project-specific basis with users of the ERR incorporating additional likelihood, impact, and RPN numbers for residual risk within the risk response section of the ERR. As users apply the ERR, it will be helpful for marine energy developers to report out on their findings from risk responses and strategies implemented. This will not only aid ERR development, but also the industry as a whole. The considerations mentioned in this section will be discussed for updates to the ERR in the future as the ERR is applied, used, and iterated on.

A key requirement for using the ERR is the need for expert evaluation. Knowledge of environmental interactions around marine energy deployments is limited, as are the experts in this field. Technology and device developers typically have a team of knowledgeable engineers for everything from power take-offs to moorings but may not have the expertise on environmental interactions and risk. Thus, while the ERR is aimed to assist them, they may still need to contract experts from research institutions or consulting companies when completing the risk assessment and interpreting the ERR. While this can add to the costs

early on in device or project design and planning, the ability to identify and track environmental risks specific to their device or project will likely save time and money for the full project schedule.

5. Conclusion

This paper highlights the methods and process used to develop a novel marine energy ERR. Development of the ERR included incorporating various aspects of engineering and environmental risk registers from several fields to create one that was fit-for-purpose for the marine energy industry to assess potential environmental risks. This process included reviews from environmental experts and several iterations with marine energy device and project developers. Two use cases, one for wave energy and another for tidal energy, were employed to demonstrate use of the ERR. Findings from the use cases were presented to show example results regarding various device components and environmental interactions (based on stressors and receptors) and show how likelihood, impact, and RPN may vary. The paper ends by highlighting applications of the ERR for the marine energy industry, acknowledging limitations of the ERR based on gaps in scientific understanding and available data on environmental effects and on the tool's novelty, and offering suggestions for future improvements to the ERR particularly as more devices are deployed and knowledge increases.

The ERR was initially developed as a tool for wave energy device developers to identify, track, and manage potential environmental interactions and associated risk of their device designs. Once the ERR was created, it was reviewed by environmental effects experts and iterated on with wave energy device developers to apply the ERR in the device design phase. Through this process, the value of the ERR for the marine energy community has come into focus and grown beyond those initial applications for wave energy device developers. The intended flexibility of the marine energy ERR has enabled the tool to be applied for various marine energy device types (e.g., wave and tidal) and both by device developers during device design and by project developers for marine energy project planning and sites under consideration for development.

Assessing risk levels does not require quantitative assessments, and risk-based approaches like the ERR and other qualitative assessments are useful for tracking and managing potential environmental risks, bringing together evidence, and advancing discussions and decision-making. The next steps for the ERR are to continue testing its application with marine energy device and project developers, refine and improve application, and address current limitations, where possible. As understanding about environmental effects of marine energy increases and uncertainties decrease with more devices deployed, it will be easier to incorporate additional considerations as seen in other risk registers (e.g., detection, residual risk). When marine energy devices and projects that have used the ERR are deployed and become operational, the lessons learned will be important to incorporate in future ERR updates, bringing additional value to the overall process of environmental risk assessment.

CRedit authorship contribution statement

Mikaela C. Freeman: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Hayley Farr:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Garrett Staines:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Joseph Haxel:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mikaela C. Freeman reports financial support was provided by U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, Office of Energy Technology, Hydropower and Hydrokinetics Office (formerly the Office of Energy Efficiency and Renewable Energy, Water Power Technologies Office). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ocecoaman.2026.108170>.

Data availability

No data was used for the research described in the article.

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