Minimizing environmental risks to progress the marine renewable energy industry

Lysel Garavelli, Deborah J. Rose, Mikaela C. Freeman, Lenaïg G. Hemery, Hayley Farr, Andrea E. Copping

Abstract—**As the marine renewable energy industry expands, consenting challenges persist due to limited knowledge of environmental effects. Since 2010, OES-Environmental has assessed these effects and developed approaches to support consenting. Risks to the environment from MRE devices can be described as stressor-receptor interactions, where stressors (devices or system components) may cause stress or injury to receptors (animals, habitats, and ecosystems). As of 2025, four interactions—changes in oceanographic systems, changes in habitat, underwater noise, and electromagnetic fields—are considered to be retired (i.e., risks unlikely to cause harm to receptors and need not be fully investigated for every project) for a small number of devices (one to six). However, entanglement, displacement, and collision risk require further study. OES-Environmental also evaluates the potential environmental effects of marine renewable energy at different scales and assesses the applicability of integrative approaches to increase the environmental acceptability of devices. While most projects focus on grid-scale power, off-grid applications (e.g., aquaculture) require smaller devices with potentially lower environmental effects. To support industry growth, marine renewable energy devices should be designed to minimize environmental risks while maximizing benefits. As the sector expands to new markets and diverse regions, balancing risks and benefits will be key to streamlining consenting and assuring sustainable deployment.**

Keywords—**Environmental effects, risk retirement, regulatory guidance, off grid uses, environmental acceptability.**

I. Introduction

As the marine renewable energy (MRE) industry continues to expand worldwide, challenges remain for consenting projects [1], due primarily to insufficient information on the potential effects on marine animals, habitats, or ecosystem processes. Since 2010, Ocean Energy Systems (OES)-Environmental, an initiative under the International Energy Agency Ocean Energy Systems, has assessed what is known about the environmental effects of MRE and developed approaches to facilitate consenting. OES-Environmental's goal is to mobilize information and international practitioners, and to coordinate scientific research that helps the industry progress in an environmentally responsible manner [2].

Risks to the environment from MRE devices are categorized as stressor-receptor interactions, where stressors are the devices or parts of the system that may cause stress, injury, or death to receptors (marine animals, habitats, and ecosystem processes). The status of knowledge of each of the seven primary stressor-receptor interactions has been examined and their pathway toward risk retirement has been assessed (Fig. 1) [3]:

- Risk of collision of marine animals with moving parts of MRE devices, generally associated with tidal, riverine, or ocean current turbines;
- Effects of underwater operational noise from MRE devices on marine animal behavior and essential sensory capabilities;
- Effects of electromagnetic fields (EMFs) from power cables and other portions of energized MRE devices on sensitive marine animals;
- Changes in benthic and pelagic habitats that support marine species;
- Entanglement of large marine animals in mooring lines or draped cables associated with MRE devices;
- Changes in oceanographic systems due to changes in ocean circulation, wave height, or energy removal;

This work was supported by the U.S. Department of Energy EERE Water Power Technologies Office to PNNL under Contract DE-AC05-76RL01830.

L. Garavelli is with Pacific Northwest National Laboratory (PNNL) Coastal Sciences Division, 1100 Dexter Avenue N, Seattle, WA 98109, USA (lysel.garavelli@pnnl.gov).

D. J. Rose is with Pacific Northwest National Laboratory (PNNL) Coastal Sciences Division, 1100 Dexter Avenue N, Seattle, WA 98109, USA (deborah.rose@pnnl.gov).

M. C. Freeman is with PNNL Coastal Sciences Division, 1100 Dexter Avenue N, Seattle, WA 98109, USA (mikaela.freeman@pnnl.gov).

L. G. Hemery is with PNNL Coastal Sciences Division, 1529 W Sequim Bay Road, Sequim, WA 98382, USA (lenaig.hemery@pnnl.gov).

H. Farr is with PNNL Coastal Sciences Division, 1100 Dexter Avenue N, Seattle, WA 98109, USA (hayley.farr@pnnl.gov).

A. E. Copping is with PNNL Coastal Sciences Division, 1100 Dexter Avenue N, Seattle, WA 98109, USA (andrea.copping@pnnl.gov).

Digital Object Identifier: https://doi.org/10.36688/ewtec-2025-1193

- Displacement of marine animals from their normal movements or migratory patterns due to the presence of MRE devices.

For each, OES-Environmental developed an evidence base, listing the key research papers and monitoring reports that define what we understand about the risks from MRE devices and a guidance document to evaluate the risk within a regulatory context. These resources have been recently updated to reflect the most current information on environmental effects as described in the OES-Environmental 2024 State of the Science Report [2]. As limited grid-scale MRE deployments and the difficulties of field monitoring in high-energy environments restrict our understanding of some of these interactions, OES-Environmental is also evaluating the potential environmental effects of MRE at different scales, as well as assessing the applicability of integrative approaches to increase the environmental acceptability of MRE devices.

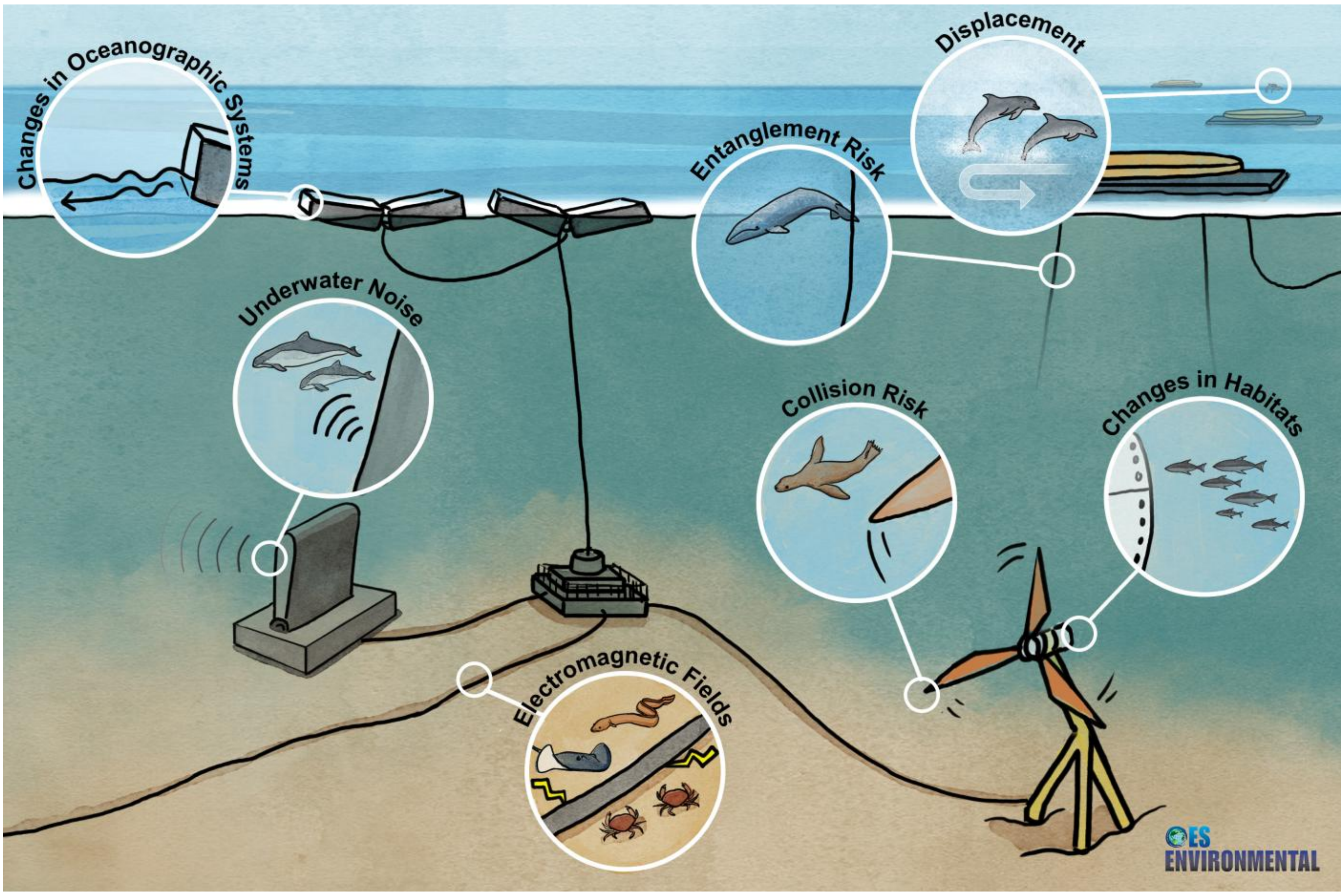

Fig. 1. Stressor-receptor interactions potentially arising from various marine renewable energy devices. (Illustration by Stephanie King)

II. ENVIRONMENTAL EFFECTS FOR SMALL NUMBERS OF MARINE RENEWABLE ENERGY DEVICES

The most recent scientific information on these stressor-receptor interactions that describe the environmental effects of MRE is summarized in the OES-Environmental 2024 State of the Science Report: Environmental Effects of Marine Renewable Energy Around the World [2]; previous versions of the report were published in 2020 [4] and 2016 [5]. Each of these reports synthesizes scientific information to present a comprehensive picture of the level of risk posed by MRE devices to the environment, as well as other information relevant to the industry.

However, provision of scientific information alone is not enough to progress deployments or enable consenting of MRE. This information must be reviewed by regulators and developers for applicability to a particular project and the level of risk must be evaluated in context, including approaches to manage risk during installation and operation. OES-Environmental has developed the risk retirement approach to aid regulators and developers in this task. Risk retirement[1] is the concept that aims to simplify consenting processes for small numbers of devices (one to six), by focusing pre-installation efforts and post-installation monitoring on environmental issues of the highest concern. Risks that

[1] More information on risk retirement is available on Tethys: https://tethys.pnnl.gov/risk-retirement

are unlikely to cause harm to marine animals or habitats, based on past scientific information and studies, can be "retired" so that additional extensive research on these topics is not needed for consenting. Regulators and MRE developers can instead rely on previously gathered information, similar consented projects, or information from analogous industries to determine levels of risk and needed mitigation or monitoring. Risk retirement does not take the place of any existing regulatory processes or replace the need for appropriate data collection before, during, and after the deployment of an MRE device.

Since the initial conception of the risk retirement process, OES-Environmental has developed supporting resources and outreach material, including reports, journal articles, conference papers, online webinars, and workshops with subject matter experts and regulators. The 2024 State of the Science Report Chapter 6 *Strategies to Aid Consenting Processes for Marine Renewable Energy* [6] describes OES-Environmental's approach to risk retirement in more detail and provides the level of risk for each stressor-receptor interaction (Table I); case studies describing how risk retirement has been applied internationally to MRE projects are also included. As of 2025, four stressor-receptor interactions are considered to be retired for small numbers of devices (one to six), based on available scientific literature and environmental monitoring (Table I) [6]: changes in oceanographic systems, changes in habitat, underwater noise, and electromagnetic fields. Other interactions will require more information to be retired: entanglement, displacement, and collision risk. Collision risk remains the main barrier to consenting new tidal and riverine energy projects [3].

TABLE I
OVERVIEW OF RISK RETIREMENT FOR EACH STRESSOR-RECEPTOR INTERACTION. [6]

STRESSOR-RECEPTOR INTERACTION	READINESS FOR RISK RETIREMENT
Collision risk	Need more information.
Underwater noise	Retired for small numbers of devices. May need to revisit as the industry moves to larger-scale arrays.
Electromagnetic fields	Retired for small numbers of devices. May need to revisit as the industry moves to larger-scale arrays.
Changes in habitat	Retired for small numbers of devices. May need to revisit as the industry moves to larger-scale arrays.
Oceanographic systems	Retired for small numbers of devices. May need to revisit as the industry moves to larger-scale arrays.
Entanglement	Need more information as the industry moves to larger-scale arrays.
Displacement	Need more information as the industry moves to larger-scale arrays.

Two key risk retirement resources have been updated in 2025: evidence bases and stressor-specific guidance documents. The evidence bases[1] comprise key documents for understanding potential effects of each stressor-receptor interaction and have been reviewed by experts, either at a conference workshop or in an online expert forum. They prioritize highly cited MRE-specific journal articles and reports focusing on field deployments. The stressor-specific guidance documents [2] compile information to help regulators, advisors, developers, and consultants determine risk, find available resources, and apply knowledge from one project to another. They provide a broad guide that can be used internationally to apply risk retirement to regulatory processes from scoping to consenting, linking scientific information to regulator concerns.

III. WHAT IS NEXT FOR ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY?

The wealth of information that has been gathered by OES-Environmental and all the cooperating researchers and developers worldwide can be used to provide more

[1] The evidence bases for all interactions are available on Tethys: https://tethys.pnnl.gov/risk-retirement-evidence-bases

[2] The stressor-specific guidance documents are available on Tethys: https://tethys.pnnl.gov/guidance-documents-stressor-specific-documents

proactive guidance to assist the MRE industry as it moves towards more deployments, including commercial arrays. This guidance should take into account the reality of the end uses for which MRE is being developed, and continue to examine the most consistent barriers to consenting and deployment.

A. Environmental effects of off-grid applications

Most environmental research and monitoring for MRE devices have sought to understand effects that will drive consenting and licensing decisions for large, grid-scale, projects. However, many near-term and likely long-term uses of MRE will be to power remote coastal and island communities, as well as to provide power at sea for offshore aquaculture, ocean observations and navigation markers, and other off-grid uses [7]. These applications will likely operate on a much smaller scale than MRE devices for regional or national grids. There has been little focus on the potential environmental effects of these increasingly more common uses for remote communities and power at sea. The smaller MRE devices required for these applications are likely to have different, and possibly lower levels of environmental effects than large-scale MRE projects [8].

It has become necessary to assess the potential environmental effects that might be expected from smaller-scale wave, tidal, and other MRE devices and projects, as well as to determine what additional information and data are needed to inform and streamline consenting for these smaller-scale projects. OES-Environmental has generated a series of hypothetical use cases for remote communities (e.g., a small coastal community, medium-size shipping port) and for power at sea (e.g., oceanographic instruments, aquaculture farms). Each use case includes: a physical description of the deployment area; details about the most appropriate MRE technology; the end uses and power needs; and a description of the local community and their values. Each use case also includes information on species that are of regulatory, commercial and/or recreational concern, important habitats, potential environmental interactions with an MRE device and infrastructure, and socio-economic benefits or concerns associated with such project. This use-case approach enables an initial assessment of potential environmental effects, based on location and scale of the projects, which could then translate into recommendations for regulatory decisions. Further research will include a comprehensive overview of the potential environmental and socio-economic effects of micro-grid and off-grid MRE applications and will lay out a path forward for addressing the remaining knowledge gaps.

B. Scaling up to arrays

Most of the knowledge on environmental effects of MRE devices has focused on single or a few (up to six) devices. The MRE industry is moving towards large arrays in particular locations; in the United Kingdom, several large-scale array projects are under development for tidal energy, such as SEASTAR led by Nova Innovation or EURO-TIDES led by Orbital Marine Power. There is a need to understand how current knowledge of environmental effects from single and small arrays of MRE devices translates to larger deployments [9].

A multi-step framework has been developed to evaluate each of the key stressor-receptor interactions for scaling up to large arrays of MRE devices [9]. While some interactions like underwater noise may scale up in a predictive manner (i.e., additive effects), other interactions such as collision risk or changes in habitat will depend on the array layout, configuration, and the site location. Understanding environmental effects for an MRE array will be complex and the effects may differ between locations. The framework provides recommendations to differentiate between perceived and real environmental risks associated with MRE development and identify knowledge gaps [9]. The framework will be used to improve our understanding of the environmental effects of large-scale arrays of MRE devices.

C. Regulator engagement

Ongoing regulator engagement is needed to ensure that the best information is readily accessible to those who oversee consenting processes. While the scientific consensus may be clear and the risk retirement process well developed, this information needs to be shared with regulators in order to translate to real-world consenting and deployment of devices. Regulator turnover and unfamiliarity with MRE devices and their potential effects hinder smooth and rapid consenting processes. Continued engagement, presentations, and development of tailored materials in support of environmental consenting and the risk retirement approach can help to bridge this gap.

OES-Environmental has regularly engaged with regulators internationally, including surveying regulators and their advisors to identify their needs and top concerns as they relate to environmental effects of MRE [10]. From this engagement, an MRE brochure[1] was developed for new or transitioning regulators to provide an overview of environmental effects. The brochure has been and will continue to be shared with US and international regulators and advisors and at opportunistic venues such as international conferences. Moving forward, OES-Environmental will update the international regulator survey in member countries to

[1] The MRE Brochure is available on Tethys: https://tethys.pnnl.gov/mre-brochure

understand the evolving needs and concerns of regulators and advisors to better support the MRE consenting process and apply risk retirement.

D. *Environmental acceptability of marine renewable energy devices*

As with any other technology, MRE devices need to be evaluated to reach commercial scale. A framework for technology evaluation and guidance of engineering activity for MRE devices was recently developed by OES [11]. This framework aims to help funders select the most promising MRE technologies using several evaluation areas such as reliability, survivability, affordability, or power capture. Another key consideration of MRE technology development is environmental acceptability.

Because extended consenting timelines are commonly related to environmental concerns, advancement of MRE technologies largely relies on minimizing interactions of devices, mooring lines, and other structures with the marine environment. With few MRE devices deployed worldwide and a large diversity of device archetypes and configurations, determining the level of these interactions and defining if devices are environmentally acceptable are challenging.

The concept of environmental acceptability for MRE is recent [11] and has not been thoroughly assessed. Environmental acceptability terminology can be found in other industries including material recycling, construction material development, water treatment, and waste management [12], [13]. In the marine environment, environmental acceptability has been used to reference the level of ecotoxicity of artificial reef material and ship ballast tanks on marine organisms [14], [15].

In the MRE context, we propose to define environmental acceptability as “Proactive guidance allowing for harnessing MRE resources efficiently while limiting the risks to the environment (marine animals, habitats, ecosystems), assuring compliance with environmental regulations, and promoting benefits”. Environmental acceptability for MRE should encompass all development phases of a device (design, deployment, operations, maintenance, decommissioning) and should be accepted by regulators, applied by developers, and used by stakeholders (e.g., funders, communities). To improve the environmental acceptability of MRE devices, OES-Environmental will focus on characterizing MRE device archetypes for wave and tidal energy, describing their specific features, and assessing how they relate to stressor-receptor interactions. Locations and regulations that apply will be compared, and potential induced benefits from MRE assessed.

IV. Conclusion

As the MRE industry progresses, OES-Environmental has continued to update its resources on risk retirement for a small number of MRE devices, focusing on producing publicly available materials. With the industry targeting new market applications and advancing toward large-scale arrays in diverse locations, including tropical and subtropical regions, the benefits and risks of a particular device, system, or array can serve as valuable design drivers. Regardless of the device archetype and geographic location, environmental acceptability will facilitate consenting processes and support the deployment of MRE systems.

Acknowledgment

We thank the following members of the OES-Environmental team and other staff at Pacific Northwest National Laboratory for their work contributing to the development of the resources described in this paper and for their contributions to understanding the level of risk for each stressor-receptor interaction: Jonathan Whiting, Kristin Jones, Marley Kaplan, Jacob McGrath, and Dominick DeCanio. We also thank the OES-Environmental member countries and their representatives for reviewing the resources and for contributing to the advancement of the MRE industry internationally.

References

[1] M. Apolonia, R. Fofack-Garcia, D. R. Noble, J. Hodges, and F. X. Correia da Fonseca, “Legal and Political Barriers and Enablers to the Deployment of Marine Renewable Energy,” *Energies*, vol. 14, no. 16, p. 4896, Aug. 2021, doi: 10.3390/en14164896.

[2] L. Garavelli, A. Copping, L. Hemery, and M. Freeman, “OES-Environmental 2024 State of the Science Report: environmental effects of marine renewable energy development around the world,” PNNL--36020, 2438585, Sep. 2024. doi: 10.2172/2438585.

[3] L. Garavelli, L. G. Hemery, D. J. Rose, H. Farr, J. Whiting, and A. E. Copping, “Marine Renewable Energy: Stressor-Receptor Interactions,” in *In L. Garavelli, A.E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World.*, Report for Ocean Energy Systems (OES), 2024, pp. 26–102. [Online]. Available: doi:10.2172/2438589

[4] A. Copping and L. Hemery, “OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World,” Ocean Energy Systems (OES), PNNL-29976, Sep. 2020. Accessed: Apr. 26, 2024. [Online]. Available: https://tethys.pnnl.gov/publications/state-of-the-science-2020

[5] A. E. Copping *et al.*, “Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the

World," Apr. 2016. Accessed: Jun. 04, 2021. [Online]. Available: https://tethys.pnnl.gov/publications/state-of-the-science-2016

[6] M. C. Freeman, "Strategies to Aid Consenting Processes for Marine Renewable Energy," in *In L. Garavelli, A.E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World.*, Report for Ocean Energy Systems (OES), 2024, pp. 170–203. [Online]. Available: doi:10.2172/2438595

[7] A. LiVecchi *et al.*, "Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets.," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy., Washington, D.C., Mar. 2019. Accessed: Dec. 26, 2023. [Online]. Available: https://tethys.pnnl.gov/publications/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets

[8] L. G. Hemery, L. Weicht, K. Jones, J. McGrath, A. E. Copping, and L. Garavelli, "Environmental effects of marine renewable energy off-grid and micro-grid applications: a use case approach to assess existing knowledge and remaining uncertainties," in *16TH European Wave and Tidal Energy Conference, 7-11 September 2025, Funchal*, 2025. doi: 10.36688/ewtec-2025-824.

[9] D. J. Hasselman *et al.*, "'Scaling up' our understanding of environmental effects of marine renewable energy development from single devices to large-scale commercial arrays," *Science of The Total Environment*, vol. 904, p. 15, Dec. 2023, doi: 10.1016/j.scitotenv.2023.166801.

[10] D. Rose, M. Freeman, and A. Copping, "Engaging the Regulatory Community to Aid Environmental Consenting/Permitting Processes for Marine Renewable Energy," *International Marine Energy Journal*, vol. 6, no. 2, pp. 55–61, Dec. 2023, doi: 10.36688/imej.6.55-61.

[11] J. Hodges *et al.*, "An International Evaluation and Guidance Framework for Ocean Energy Technology," IEA-OES, Oct. 2023. Accessed: May 15, 2024. [Online]. Available: https://tethys.pnnl.gov/publications/international-evaluation-guidance-framework-ocean-energy-technology

[12] M. Durić *et al.*, "Environmental Acceptability of Geotechnical Composites from Recycled Materials: Comparative Study of Laboratory and Field Investigations," *International Journal of Environmental Research and Public Health*, vol. 20, no. 3, Art. no. 3, Jan. 2023, doi: 10.3390/ijerph20032014.

[13] P. S. Dange and R. K. Lad, "A fuzzy rule based system for an environmental acceptability of Sewage Treatment Plant," *KSCE Journal of Civil Engineering*, vol. 21, no. 7, pp. 2590–2595, Nov. 2017, doi: 10.1007/s12205-017-1504-y.

[14] J. Santos *et al.*, "Assessment of the environmental acceptability of potential artificial reef materials using two ecotoxicity tests: Luminescent bacteria and sea urchin embryogenesis," *Chemosphere*, vol. 310, p. 136773, Jan. 2023, doi: 10.1016/j.chemosphere.2022.136773.

[15] S. La Carbona *et al.*, "Efficacy and environmental acceptability of two ballast water treatment chemicals and an alkylamine based-biocide," *Science of The Total Environment*, vol. 409, no. 2, pp. 247–255, Dec. 2010, doi: 10.1016/j.scitotenv.2010.10.006.