A guide for co-locating marine energy and aquaculture

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Abstract—**In recent years, there has been increasing interest in using marine energy for non-grid applications, such as powering at-sea uses in areas where adequate marine energy resources exist. One of these uses is aquaculture, which is a growing sector in both offshore and coastal regions internationally. As both marine energy and aquaculture progress, there is an opportunity to bring these industries for mutual advancement. Aquaculture provides a new market for marine energy, especially one that is viable for smaller-scale technologies. Marine energy provides a source of renewable energy that is created on site, helping move the aquaculture industry toward more sustainable practices and away from diesel-based energy for at-sea activities. Co-locating and powering aquaculture with marine energy within the same space and time scales can lead to increased markets for marine energy and sustainable development. Because aquaculture is still a new application of marine energy, there are many unknowns and potential barriers that need to be overcome to make co-location a reality. We have developed a *Guide for Co-location of Marine Energy and Aquaculture* to provide guidance for considering a co-located project and to begin to answer some of these questions and remaining challenges.**

Keywords—**Aquaculture, marine energy, co-location**

I. Introduction

Marine energy is energy generated from waves, tides, currents, and salinity or thermal gradients. Worldwide, there is great potential to harvest energy from the ocean. Marine energy has traditionally been thought of as supplying power to the grid, but there has been increasing interest in using marine energy for non-grid uses, such as providing power at sea for activities located in areas where adequate marine energy resources exist [1]. One of these uses is aquaculture, which is also a growing sector. This paper focuses on marine aquaculture, referring to the farming of marine organisms (including fish, shellfish, crustaceans, and seaweed) in the ocean (both nearshore and offshore waters) or in coastal areas.

As both marine energy and aquaculture progress, there is an opportunity to bring together these uses to further advancement of each industry. This is called co-location, where marine uses (aquaculture and marine energy in this case) are developed within the same space and time scale [2], [3]. For the purposes of this effort, co-location specifically includes integrating and powering aquaculture with wave energy. Co-location may offer several opportunities for both the aquaculture and marine energy sectors [4]. For example, aquaculture can provide a new market for marine energy developers to explore, especially one that is viable for smaller-scale marine energy technologies [5]. Additionally, marine energy can provide a source of secure renewable energy that is created on site, helping move the aquaculture industry toward in-situ power generation for energy independence and lower production costs [6].

While this opportunity exists, co-location of aquaculture and marine energy is still a novel application and requires understanding its feasibility to bring this to fruition. Several research or pilot projects have shown the viability of co-location [4], [7] but this has yet to be thoroughly tested at scale and over the long term. Knowledge gaps remain to further the understanding of the feasibility for co-location. For example, in the United States (US) both marine energy and aquaculture have been slow to develop particularly due to consenting challenges [8], [9] requiring an understanding of the regulatory regimes that must be navigated to see a co-located deployment come to life. Costs and benefits of co-locating aquaculture with another industry are also complex to evaluate, and concerns remain about the potential cumulative impacts on the environment [10]. Technical feasibility, such as how to engineer and integrate a co-located system, must also be explored, both through desk-based research like spatial analyses to

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identify areas viable for co-location [11] as well as through demonstration projects to test concepts and work towards full-scale developments. Energy needs of aquaculture operations also need to be better understood to identify what types of marine energy technologies are best suited for different aquaculture systems. Importantly, social aspects (e.g., community context and perspectives, etc.) must be accounted for to comprehensively understand the viability of future co-location [4], [12].

The *Guide for Co-location of Marine Energy and Aquaculture* has been developed to provide guidance for considering a co-location project and begin to answer some of these questions and remaining challenges. It is intended for aquaculture operators and marine energy technology developers, particularly those interested in partnering to co-locate joint aquaculture and marine energy developments. This guide aims to offer insight based on several years of research at Pacific Northwest National Laboratory to explore the feasibility of co-location. The paper presents an overview of the guide in development and includes excerpts from it to highlight key steps and progress to-date.

II. Considerations for Co-location

In order to co-locate marine energy and aquaculture, many aspects need to be considered (Fig. 1). These are detailed in the following sections.

Fig. 1. Key considerations for co-locating aquaculture and marine energy.

A. Define potential project

Beginning any project requires defining details and attributes. For co-location, the first step will be to define the project characteristics, likely starting with the aquaculture operation and its energy requirements. Aquaculture systems may vary from growing single species of fish, shellfish, crustaceans, or seaweed to integrated multi-trophic systems that grow multiple species from different tropic levels. For aquaculture, the structures used may vary greatly. For example, long lines with bags or cages, floating upweller systems, docks, platforms with oyster tumblers, nursery tanks, or floating or submersible net pens.

After defining the aquaculture system and its energy requirements, marine energy technologies can be assessed to find a device that would be fit for purpose. There are a variety of available marine energy technologies [13], making it theoretically possible in many cases to select a specific technology most appropriate for pairing with the defined aquaculture operation. Marine energy technologies and their suitability will vary based on available resources and the location of the aquaculture system. Table I details the various marine energy types and their suitability for offshore aquaculture. For co-location, it will also need to be decided if the marine energy system will consist of one device or an array of devices, which will depend on the size and energy needs of the aquaculture system [14].

Another component of defining a potential project includes identifying the appropriate consenting or regulatory regime that will be used. This includes the overall consenting process for siting and authorization, important considerations for the project to document or assess (e.g., water quality parameters, protected or sensitive habitats, or lease requirements), and government agencies or organizations to coordinate or communicate with. This will help in later steps as a project gets ready to navigate regulatory processes and apply for consents and authorization. It should be noted that while navigating the regulatory regime is the final key consideration in the guide, the process begins in earlier steps including identifying the regulatory regime and incorporating regulatory parameters in suitability assessments.

B. Identify key attributes

Next, key attributes for co-location need to be identified. A framework for co-locating offshore aquaculture and wave energy was developed to help consider, evaluate, and prioritize goals, objectives, and parameters for co-location (Fig. 2). This framework uses a multi-criteria decision-making approach, a method for evaluating a variety of criteria and objectives to aid decision-making in complex systems. Multi-criteria

TABLE I
POTENTIAL ADVANTAGES AND DISADVANTAGES OF MARINE ENERGY FOR OFFSHORE AQUACULTURE. ADAPTED FROM FREEMAN ET AL. [2].

Marine Energy	Potential advantages of aquaculture	Potential challenges for aquaculture
Wave Energy	• Suitable for onshore, nearshore, and offshore aquaculture sites.	• High cost of technology installation for large devices. • Resource variability and intermittency. • High-energy sites may not be ideal/suitable for certain types of aquaculture operations.
Tidal Stream	• Resource predictability and power scheduling with a high degree of accuracy. • Resources available year-round. • Suitable for onshore and nearshore aquaculture sites • Natural water flow at sites may facilitate flushing of organic waste from aquaculture. • Baseload power is possible.	• High cost of technology installation • High-energy sites may not be ideal/suitable for certain types of aquaculture operations.
Ocean Current	• Resource predictability and power scheduling with a high degree of accuracy. • Resources available year-round. • Suitable for onshore and nearshore aquaculture sites. • Natural water flow at sites may facilitate flushing of organic waste from aquaculture. • Baseload power is possible.	• High cost of technology installation. • Remoteness of some offshore sites may increase operating expenses. • High energy sites may not be ideal/suitable for certain types of aquaculture operations.
Ocean Thermal Energy Conversion	• Resource predictability and power scheduling with a high degree of accuracy. • Resources available year-round. • Suitable for onshore and nearshore aquaculture sites • Natural water flow at sites may facilitate flushing of organic waste from aquaculture. • Baseload power is possible. • Infrastructure could be used to implement feeding systems and other components of aquaculture installations that require platforms	• High cost of technology installation. • Only suitable in tropical and subtropical regions.
Salinity Gradient	• Resource predictability and power scheduling with a high degree of accuracy. • Suitable for nearshore areas. • Can provide access to freshwater, saltwater, and brackish water. • Baseload power is possible.	• High cost of technology installation. • Technology still in early stages of development.

decision-making approaches have often been used for energy and sustainability assessments [7], [8] and energy siting assessments [15], [16] as they can capture the complexity of different technical, economic, environmental, and social aspects. The framework developed focuses on key environmental, regulatory, and logistical parameters to inform spatial analyses to aid identification of suitable areas for co-location. However, a variety of economic and social factors important for siting (e.g., employment, supply chain, social acceptance, governance, etc.) were not included due to spatial analysis limitations. Figure 2 provides an example for the co-location of aquaculture and marine energy, with parameters specific to offshore aquaculture and wave energy; other goals, objectives, and parameters may be relevant for specific co-located projects and should therefore be considered in decision-making. Overall, the framework can help aquaculture operators and wave energy developers assess how key attributes align for both industries.

C. Find suitable areas

Finding suitable areas to co-locate marine energy and aquaculture is another important step in assessing feasibility, particularly because traditionally, aquaculture operations are sited in low-energy, protected environments – areas that are likely not viable for marine energy. With offshore aquaculture for example, the industry is moving into high-energy environments that may be suitable for marine energy. In nearshore areas, there may also be opportunities for new marine energy technologies to harvest energy in lower-resource environments, such as low-current velocity devices that may be well suited [17]. It is important to detail key attributes and associated parameters to consider for co-location to find suitable areas where both activities can optimally function. Garavelli et al. [11] identified suitable locations for co-locating wave energy and offshore aquaculture in the US through spatial analysis. In this study, the authors defined the key environmental, regulatory, and logistical parameters to consider for co-location and their associated constraints (e.g., depth range, wave height range, etc.) [18], [19]. The framework (Fig. 2) can be used to help define priority parameters for co-location based on the goals and objectives of the project.

Once suitable areas for co-location have been identified, a specific site needs to be selected. To do so, site-specific characteristics will need to be defined, and environmental assessments will likely need to be carried out, particularly to collect data on key parameters. Several site-specific characteristics overlap between marine energy and aquaculture, such as depth, current speed, and wave height. Others are particularly important for aquaculture, like nutrients, dissolved oxygen, or temperature, and will be dependent on the species grown within the aquaculture operation. Overlapping needs for environmental assessments and data collection provide an opportunity for co-located deployments, which can aid in confirming the suitability of a location, informing consenting processes, and lowering costs through shared data collection.

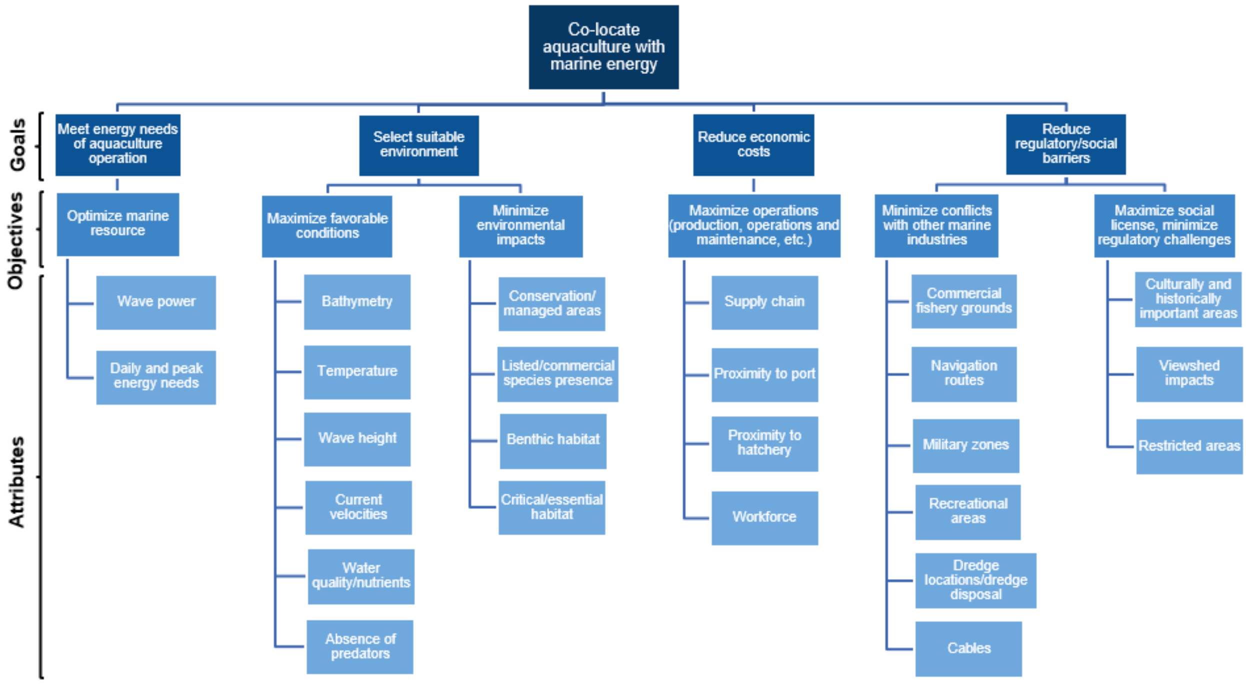

Fig. 2. Multi-criteria decision analysis objective tree to assess co-location of aquaculture and marine energy based off example goals, objectives, and parameters for co-location of offshore aquaculture and wave energy.

D. *Detail integration*

Physical and electrical integration of marine energy devices and aquaculture systems are also key knowledge gaps for co-location. Davonski [14] provides insight into this topic, specifically for an offshore integrated multi-trophic aquaculture system with wave energy. Technical considerations for co-location include energy supply and storage, the ability to withstand extreme environmental conditions with adequate moorings for both the aquaculture and wave energy system, and the proximity of the infrastructure. The variability of aquaculture and wave energy technologies and site characteristics will need to be considered for a safe and reliable co-located deployment. The operations and management of both aquaculture and wave energy will require each system to work on their own but also to be integrated. For example, minimizing downtime and maintenance of the marine energy system is essential, as aquaculture farms operate daily, and certain species, such as fish, require continuous monitoring. To advance understanding of integration, there will be a need to work towards pilot or demonstration projects [20]. Such projects should answer these key integration needs and remaining questions. In particular, opportunities for integration should be further explored to detail if and when aquaculture and marine energy systems can be integrated into one shared structure or if there is a need to have separate but connected systems.

E. Stakeholder perspectives

Throughout project development, it is necessary to consider stakeholder and community perspectives. Ideally, any project includes stakeholders from the outset, understanding community values and contexts so that a co-located project can maximize benefits to a community and minimize negative impacts [21].

A few key findings from stakeholder engagement efforts carried out around this co-location research over the last few years include the need to:

1) Assess feasibility for co-location comprehensively, including considerations beyond only aquaculture and marine energy, such as social and economic effects, supply chain, workforce, jobs, education, environmental effects, and more. This also requires balancing various perspectives and needs (e.g., community/local, technical, business, environmental).
2) Understand lessons learned from previous developments in a location, both aquaculture and marine energy as well as other infrastructure projects, to learn from, and in particular to avoid past challenges or adverse impacts.
3) Prioritize engagement with stakeholders and local communities, to learn from them and incorporate their perspectives. Additionally, explore synergies such as fishing or tourism around co-location and potential benefits like food security.
4) Incorporate location-specific needs and challenges as part of feasibility assessments, and apply community-led, participatory approaches with transparent communication. Ideally, a co-located project will include meaningful community involvement throughout the planning, siting, and development process.

Last, it may be of interest for communities to have co-located aquaculture and marine energy projects that are proven from a technological and integration perspective before being deployed, particularly in communities with strong ties to the coast and ocean or histories of challenges with industry and development. This increases the importance of developing demonstration or pilot projects prior to full-scale deployments to be able to test uncertainties and iterate on technical aspects before getting communities involved [22], [23], [24].

III. Remaining Needs

While progress has been made to work towards co-located aquaculture and marine energy deployments, there are remaining needs that need to be understood. These include:

- Understanding energy needs of aquaculture operations, particularly of various aquaculture systems as energy use varies widely,
- Demonstrating the integration of aquaculture and marine energy infrastructure and sharing lessons learned,
- Elucidating unknowns regarding insurance and liability, and
- Analyzing potential costs.

A reasonable approach to answering these questions is using pilot or demonstration projects to address needs. It is unlikely that all needs will be answered at the start, but rather a phased approach may be best. First, starting with several pilot or demonstration projects as proof of concept for co-locating and integrating various aquaculture and marine energy systems. For example, in Scotland, a fish farm and a wave energy device were successfully co-located [4]. This demonstration highlighted the potential for co-location, particularly as the wave energy device provided power for the 18-month deployment without interfering with the aquaculture system. Additionally, battery storage systems were used to help address 24/7 power needs.

Similar deployments that begin to answer the key needs for co-location can help greatly advance understanding of the feasibility. This will require collaboration and partnership between marine energy developers and aquaculture operators, likely with researchers acting as facilitators during the early stages of pilot/demonstration projects to help bring together these two industries and share knowledge across domains. Once proof-of-concept is shown, more nuanced questions like insurance and liability can begin to be understood. There will likely not be a one-size-fits-all approach to these decisions, but rather fit-for-purpose solutions that can highlight successful attributes for co-located deployments.

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References

[1] 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. Available: https://tethys.pnnl.gov/publications/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets

[2] M. F. Schupp *et al.*, "Toward a Common Understanding of Ocean Multi-Use," *Front. Mar. Sci.*, vol. 6, Apr. 2019, doi: 10.3389/fmars.2019.00165.

[3] C. M. Gonzales, S. Chen, and H. E. Froehlich, "Synthesis of multinational marine aquaculture and clean energy co-location," *Front. Aquac.*, vol. 3, Aug. 2024, doi: 10.3389/faquc.2024.1427839.

[4] M. Freeman, L. Garavelli, E. Wilson, M. Hemer, M. L. Abundo, and L. E. Travis, "Offshore aquaculture: a market for ocean renewable energy," Ocean Energy Systems (OES), Apr. 2022. Available: https://tethys.pnnl.gov/publications/offshore-aquaculture-market-ocean-renewable-energy

[5] R. Branch, D. Rose, M. Grear, C. Briggs, and F. Ticona Rollano, "Powering the Blue Economy: Marine Energy at Kelp Farm Sites," *Marine Technology Society Journal*, vol. 57, no. 4, pp. 6–14, Dec. 2023, doi: 10.4031/MTSJ.57.4.2.

[6] H. P. Nguyen and C. M. Wang, "Advances in Offshore Aquaculture and Renewable Energy Production," *Journal of Marine Science and Engineering*, vol. 12, no. 9, Art. no. 9, Sep. 2024, doi: 10.3390/jmse12091679.

[7] D. Clemente, P. Rosa-Santos, T. Ferradosa, and F. Taveira-Pinto, "Wave energy conversion energizing offshore aquaculture: Prospects along the Portuguese coastline," *Renewable Energy*, vol. 204, pp. 347–358, Mar. 2023, doi: 10.1016/j.renene.2023.01.009.

[8] S. E. Lester *et al.*, "Diverse state-level marine aquaculture policy in the United States: Opportunities and barriers for industry development," *Reviews in Aquaculture*, vol. 14, no. 2, pp. 890–906, 2022, doi: 10.1111/raq.12631.

[9] M. C. Rubino, "Policy Considerations for Marine Aquaculture in the United States," *Reviews in Fisheries Science & Aquaculture*, vol. 31, no. 1, pp. 86–102, Jan. 2023, doi: 10.1080/23308249.2022.2083452.

[10] L. Falconer *et al.*, "Planning and licensing for marine aquaculture," *Reviews in Aquaculture*, vol. 15, no. 4, pp. 1374–1404, 2023, doi: 10.1111/raq.12783.

[11] L. Garavelli, M. C. Freeman, L. G. Tugade, D. Greene, and J. McNally, "A feasibility assessment for co-locating and powering offshore aquaculture with wave energy in the United States," *Ocean & Coastal Management*, vol. 225, p. 106242, Jun. 2022, doi: 10.1016/j.ocecoaman.2022.106242.

[12] Turschwell M.P. et al., "4.20.003 Tools to assess cross-sector interactions - Final Project Report," Blue Economy Cooperative Research Centre, 2020. Available: https://blueeconomycrc.com.au/wp-content/ uploads/2021/10/BECRC_SSS-4.20.003_A4_LR2.pdf

[13] A. E. Copping, L. G. Hemery, H. Viehman, A. C. Seitz, G. J. Staines, and D. J. Hasselman, "Are fish in danger? A review of environmental effects of marine renewable energy on fishes," *Biological Conservation*, vol. 262, p. 13, 2021, doi:10.1016/j.biocon.2021.109297.

[14] Z. Davonski, "Considerations for a Co-located Aquaculture and Wave Energy Deployment: Integration and Energy Preliminary Assessment.," Report in support of PNNL's research: Co-locating Wave Energy with an Integrated Multi-trophic Aquaculture System., 2024. Available: https://tethys-engineering.pnnl.gov/publications/considerations-co-located-aquaculture-wave-energy-deployment-quantifying-demand

[15] Z. Barr, J. Roberts, W. Peplinski, A. West, S. Kramer, and C. Jones, "The Permitting, Licensing and Environmental Compliance Process: Lessons and Experiences within U.S. Marine Renewable Energy," *Energies*, vol. 14, no. 16, Art. no. 16, Jan. 2021, doi: 10.3390/en14165048.

[16] B. M. Hurley, K. L. Oremus, and A. M. Birkenbach, "Testing the waters: the state of U.S. shellfish permitting regulations," *Anim Front*, vol. 14, no. 4, pp. 28–31, Sep. 2024, doi: 10.1093/af/vfae016.

[17] R. Branch *et al.*, "Low tidal current speed electricity generation for power at an aquaculture farm," Dec. 2023, doi: 10.5281/ZENODO.10265459.

[18] S. E. Lester *et al.*, "Marine spatial planning makes room for offshore aquaculture in crowded coastal waters," *Nat Commun*, vol. 9, no. 1, p. 945, Mar. 2018, doi: 10.1038/s41467-018-03249-1.

[19] S. Møller, "Reduction of CO2 Emissions in the Salmon Farming Industry: the Potential for Energy Efficiency Measures and Electrification.," Master Thesis, Norwegian University of Science and Technology, 2019. Available: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2624655.

[20] H. M. Jansen *et al.*, "The feasibility of offshore aquaculture and its potential for multi-use in the North Sea," *Aquacult Int*, vol. 24, no. 3, pp. 735–756, Jun. 2016, doi: 10.1007/s10499-016-9987-y.

[21] D. J. Rose and M. C. Freeman, "Stakeholder Engagement 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. 144–169. doi:10.2172/2438593

[22] K. A. Abhinav *et al.*, "Offshore multi-purpose platforms for a Blue Growth: A technological, environmental and socio-economic review," *Science of The Total Environment*, vol. 734, p. 138256, Sep. 2020, doi: 10.1016/j.scitotenv.2020.138256.

[23] A. I. Manolache and G. Andrei, "A Comprehensive Review of Multi-Use Platforms for Renewable Energy and Aquaculture Integration," *Energies*, vol. 17, no. 19, Art. no. 19, Jan. 2024, doi: 10.3390/en17194816.

[24] D. Depellegrin *et al.*, "Exploring Multi-Use potentials in the Euro-Mediterranean sea space," *Science of The Total Environment*, vol. 653, pp. 612–629, Feb. 2019, doi: 10.1016/j.scitotenv.2018.10.308.