

Guide for Co-locating Aquaculture and Marine Energy

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Table of Contents

Introduction 1

Considerations for Co-location 4

1. Define Potential Project 5

2. Identify Key Attributes 12

3. Find Suitable Areas 14

Case Study: Finding Suitable Areas for Nearshore Co-Location 17

4. Integrate Systems 18

5. Navigate Regulatory Regime 19

Case Study: Navigating the Regulatory Regime in Puerto Rico 23

Understand Perspectives 24

Remaining Research Needs 25

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Introduction

Marine energy is energy generated from waves, tides, ocean and river currents, and salinity or thermal gradients (**Figure 1**). In the United States (US), there is great potential to harvest energy from these sources. Marine energy is a developing sector and has traditionally been thought of as supplying power to the main electrical grid. However, in recent years, there has been increasing interest in using marine energy for other uses, such as providing power at sea in areas where adequate marine energy resources exist. One of these uses is marine aquaculture (also known as mariculture), which is also a developing sector in both offshore and coastal areas worldwide. In this report, aquaculture is defined as the farming or cultivation of marine species (fish, shellfish, seaweed, etc.). This cultivation often has off-grid or on-water energy needs that could be fulfilled by marine energy, in theory – though this is still an area of active research[1,2]. As both the marine energy and aquaculture industries progress, there is an opportunity to bring together these industries for mutual advancement. This is called co-location, where marine uses (aquaculture and marine energy in this case) are developed and operated within the same space and timeframe. In this document, co-location also includes integrating and powering aquaculture with marine energy (**Figure 2**). Aquaculture provides a new market opportunity for the marine energy sector to explore, especially one that is viable for small-scale wave and tidal energy technologies. Marine energy could provide a source of secure energy that is produced on site or nearby, helping the aquaculture industry move toward in-situ power generation for energy independence and possibly lower production costs. It could also potentially avoid or mitigate effects from typical energy generation sources, including fewer negative environmental effects that may be material to permitting and environmental review and social license or public perceptions. However, more research is needed to fully understand the implications for marine energy and aquaculture co-location.

[1] Garavelli et al. (2025). Suitability for co-location of offshore aquaculture and wave energy in the US Caribbean. *Environmental Research Letters,* http://doi.org/10.1088/1748-9326/ae0805

[2] Cao et al. (2025). A Review of Marine Renewable Energy Utilization Technology and Its Integration with Aquaculture. *Energies* 18: 2343. https://doi.org/10.3390/en18092343

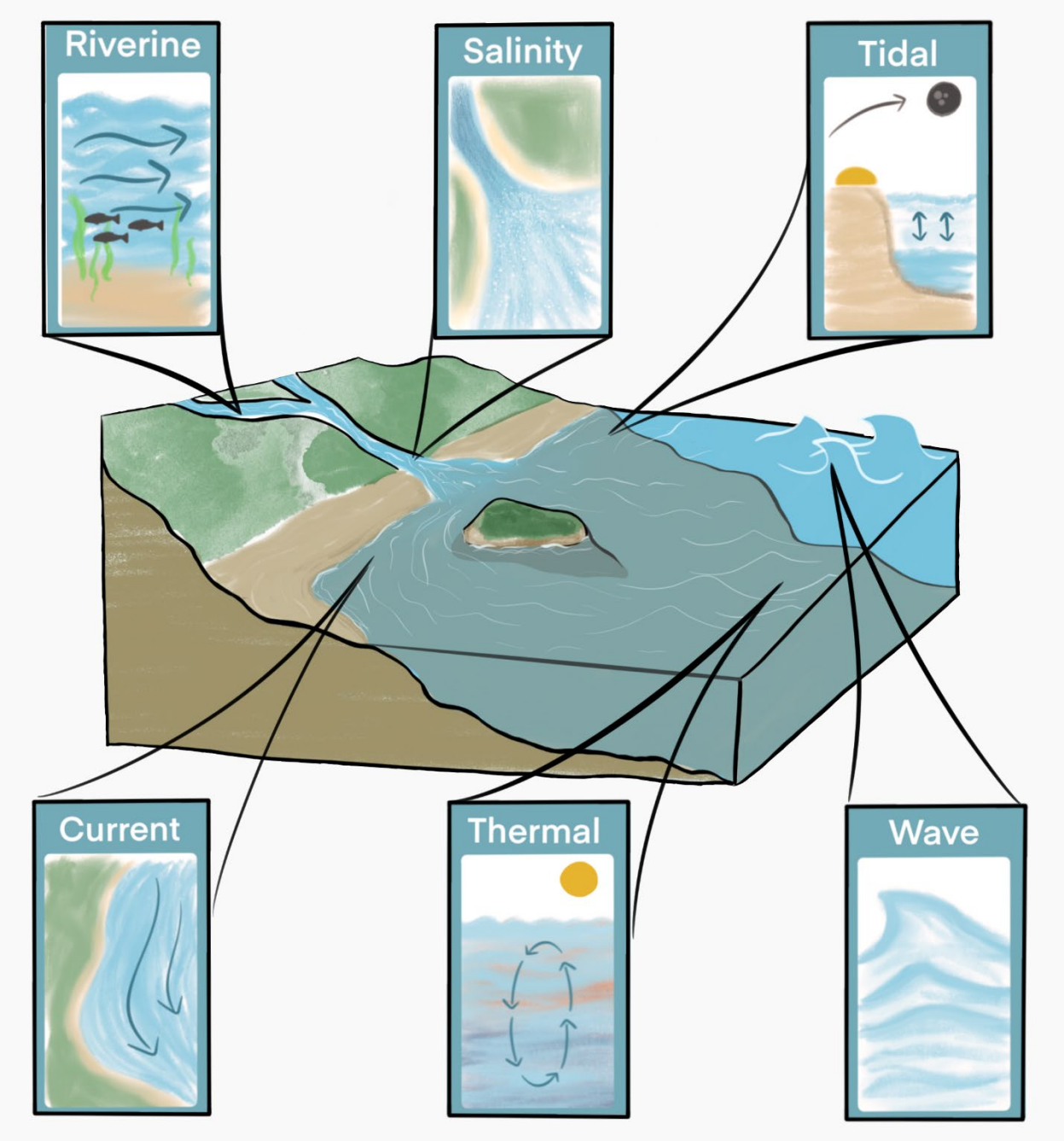


Figure 1. Example illustration showing where each type of marine energy resource can typically be found. Illustration by Candace Briggs, Pacific Northwest National Laboratory.

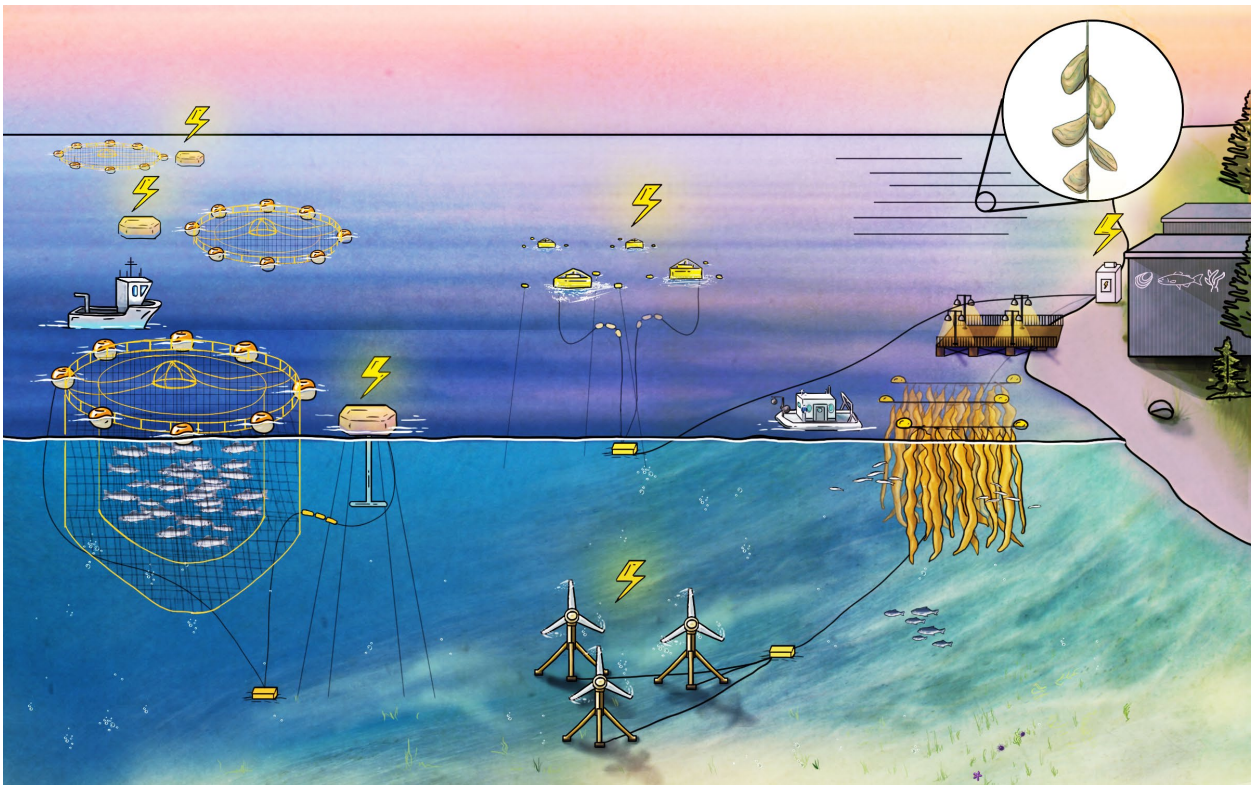


Figure 2. Various imagined examples of co-located marine energy devices and aquaculture facilities. (Illustration by Stephanie King, Pacific Northwest National Laboratory).

While the opportunity for co-locating aquaculture and marine energy exists, it is a novel application and requires understanding its feasibility to bring it to fruition. Several studies or pilot projects worldwide have shown the viability of co-location (Freeman et al. 2022[3]), and there is still more research and testing needed to see co-location of aquaculture and marine energy implemented over the long term.

[3] Freeman et al. (2022). Offshore Aquaculture: A Market for Ocean Renewable Energy. https://www.ocean-energy-systems.org/publications/oes-documents/market-policy-/document/offshore-aquaculture-a-market-for-ocean-renewable-energy./

This **Guide for Co-location of Marine Energy and Aquaculture** (hereafter the Guide) has been developed by the Pacific Northwest National Laboratory (PNNL) to provide guidance for developing co-location projects and methods to simplify the approach. It is intended for aquaculture operators and marine energy technology developers, particularly those interested in partnering to co-locate new aquaculture and marine energy[4] developments. The Guide is focused on co-locating a new joint project and planning from the outset with both industries but can also be applicable to incorporating marine energy into existing aquaculture operations (Branch et al. in prep[5], Branch et al. 2023[6]). It aims to offer insight based on several years of research at PNNL to explore the feasibility of co-location. The Guide focuses on wave and tidal energy as these technologies are well suited for various types and scales of aquaculture operations. While the Guide provides information on aquaculture and marine energy, it does not replace regulatory guidance for either industry. Engaging with relevant agencies throughout the planning and permitting process is essential to provide the most accurate information for a specific project.

The Guide outlines considerations for co-location from both aquaculture and marine energy perspectives and includes a framework for assessing co-location potential. Case studies demonstrate approaches to application and real-world examples, and key research gaps are highlighted as remaining needs to move both industries forward together.

Considerations for Co-location

In order to co-locate marine energy and aquaculture, many aspects need to be considered (**Figure 3**). These are detailed in the following sections.



Figure 3. Considerations for co-location. These steps may occur in this sequence, concurrently, or can be iterative. For instance, while "navigate regulatory regime" is shown at the end, there are likely to be aspects of permitting/regulatory efforts that will be included in other steps.

[4] While some aquaculture systems have considered co-location with offshore wind energy, the Guide considers marine energy to only include energy generated through the movement of water or harnessing gradients and does therefore not include offshore wind energy.
[5] Branch et al. (in prep). Powering the Coastal Economy: Marine Energy at Shellfish Farms. *Link to publication and journal information will be included when available.*
[6] Branch et al. (2023). Powering the Blue Economy: Marine Energy at Kelp Farm Sites. *Marine Technology Society Journal* 57(4): 6-14. https://doi.org/10.4031/MTSJ.57.4.2

1. Define Potential Project

Since the goal of co-location is to power the aquaculture infrastructure, a clear understanding of the infrastructure design and limitations is needed to identify the appropriate marine energy technology for coupling. The first step is defining the project details and attributes, starting with the planned or existing aquaculture operation and specifying its current and expected future energy requirements. Aquaculture systems may vary from growing single species of finfish, shellfish, or seaweed to integrated multi-trophic systems that grow multiple species from different trophic levels. For each type of aquaculture system, the structures used and energy needs may vary greatly. For example, long lines, bags, cages, floating upweller systems, docks, platforms with oyster tumblers, or floating or submersible net pens may be used across various coastal or offshore applications. For more information and examples, see The Technical Guide to Marine Aquaculture Gear (NOAA 2025[7]). Some example illustrations are shown in **Figure 4**.

After defining the aquaculture system, marine energy technologies can be assessed to identify those that would meet the required energy. Suitability of marine energy technologies will vary based on available energy resources, energy needs, environmental factors, and the location and physical characteristics of the aquaculture system, as shown in **Table 1**. There are a variety of available marine energy technologies[8] (some examples shown in **Figure 5**), making it necessary to select a specific technology most appropriate for pairing with the defined aquaculture operation. To address aquaculture energy demands, it will also be necessary to determine 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 (Davonski 2024[9]) as well as available energy resources and other existing activities. Some aquaculture systems have considered co-location with offshore wind turbines, but the focus of this Guide is on wave and tidal energy.

[7] National Oceanic and Atmospheric Administration. (2025). The Technical Guide to Marine Aquaculture Gear. https://repository.library.noaa.gov/view/noaa/71156

[8] Examples of each type of marine energy technologies are available on PRIMRE: https://openei.org/wiki/PRIMRE/Basics

[9] Davonski, Z. (2024). Considerations for a Co-located Aquaculture and Wave Energy Deployment: Quantifying Demand and Assessing Integration. Report in support of PNNL's research. https://www.pnnl.gov/publications/considerations-co-located-aquaculture-and-wave-energy-deployment-quantifying-demand

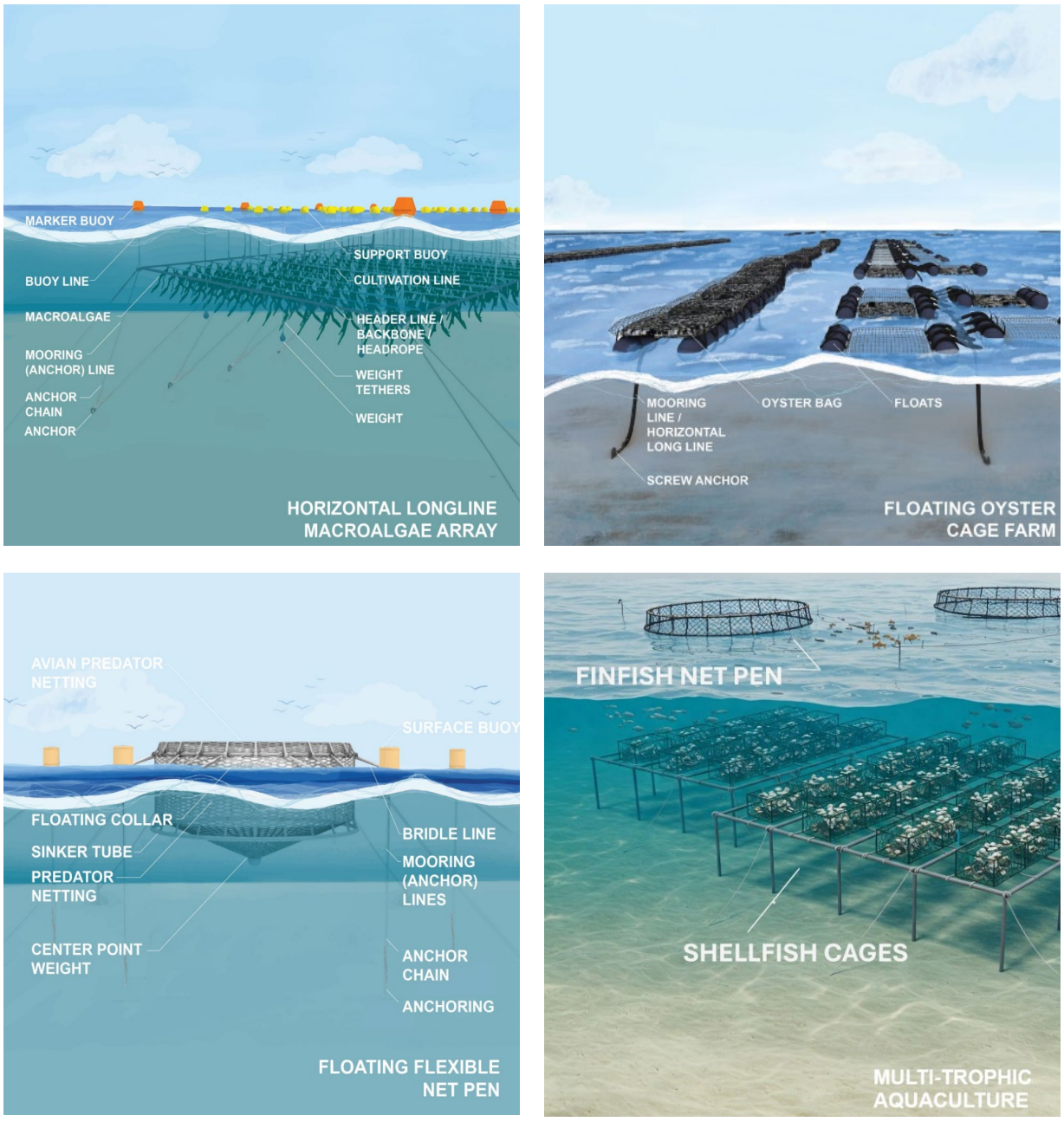
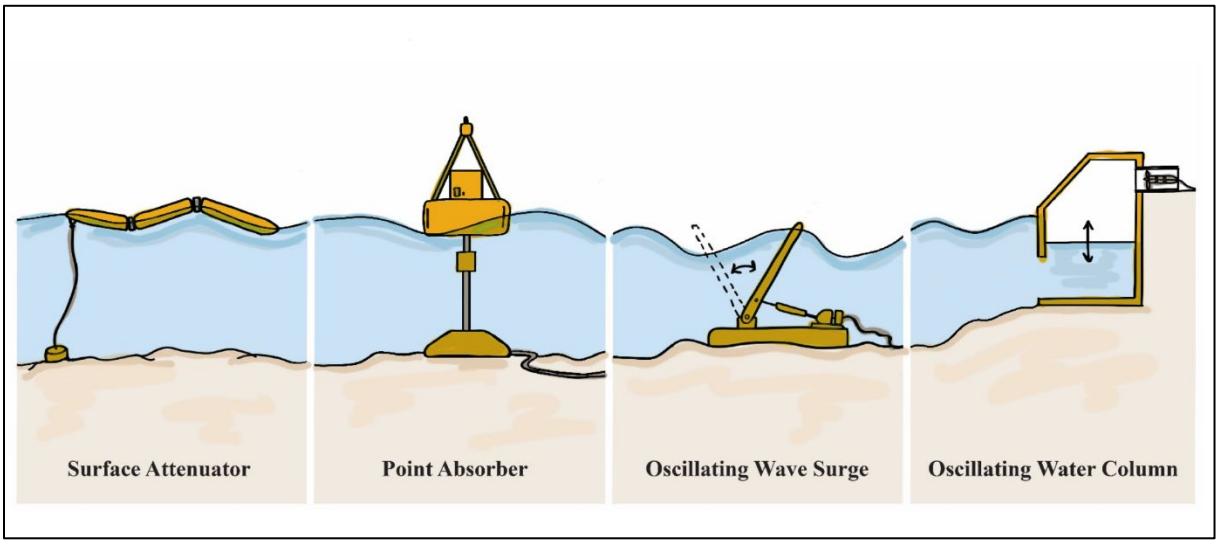


Figure 4. Example illustrations of gear types for macroalgae, shellfish, multi-trophic, and finfish aquaculture (clockwise). From NOAA 2025[7].

Example wave energy technologies



Example tidal / current energy technologies

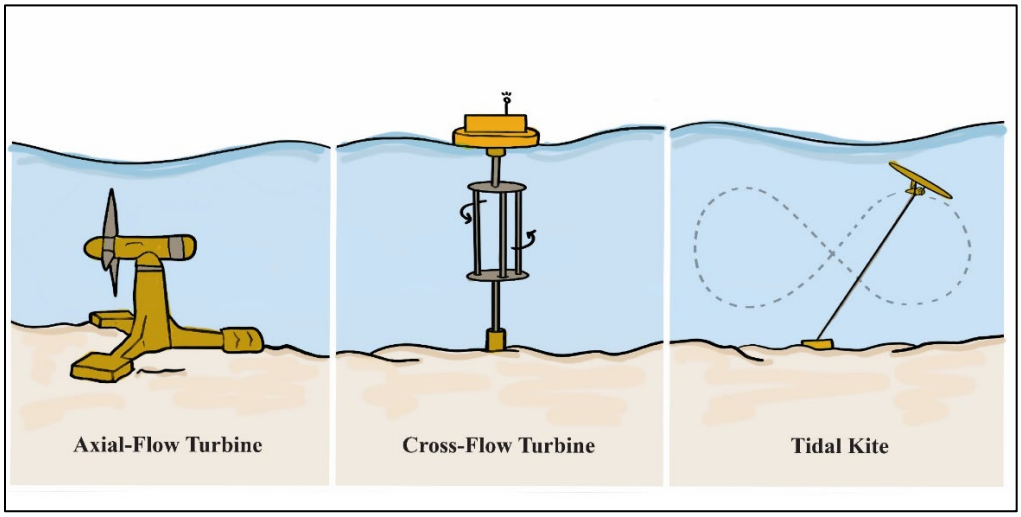


Figure 5. Example illustrations of marine energy technologies, from the Marine Energy Illustration Library[10]. Illustrations by Cailene Gunn, Pacific Northwest National Laboratory. Additional information on marine energy technologies is available on PRIMRE[8].

[10] Examples of various marine energy technologies and other illustrations related to marine energy are available in the Marine Energy Illustration Library on Tethys Engineering: https://tethys-engineering.pnnl.gov/illustration-library

Table 1. Potential advantages and challenges of various marine energy technologies for aquaculture, including which may be best suited to different types of aquaculture. (Adapted from Freeman et al. 2022[3]).

Technology	Potential Advantages for Aquaculture	Potential Challenges for Aquaculture
Wave	• Suitable for onshore, nearshore, and offshore aquaculture systems. • Natural water flow at sites may facilitate flushing of organic waste from aquaculture or provide nutrients. • Possible sheltering effect of wave energy technology to an aquaculture farm located downwave. • Enables farms to be sited offshore which may reduce conflicts with other marine uses.	• High cost of technology installation for large devices compared to conventional energy supply. • Resource variability and intermittency. • Higher-energy sites may not be ideal/suitable for certain types of aquaculture systems. • Technical and commercial readiness level of existing technologies.
Tidal	• 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 or provide nutrients. • Baseload power is possible.	• High cost of technology installation compared to conventional energy supply. • Higher-energy sites may not be ideal/suitable for certain types of aquaculture systems. • Technical and commercial readiness level of existing technologies.
Ocean Current	• Resource predictability and power scheduling with a high degree of accuracy. • Resources available year-round. • Suitable for offshore, onshore, and nearshore aquaculture sites. • Natural water flow at sites may facilitate flushing of organic waste from aquaculture or provide nutrients. • Baseload power is possible. • Enables farms to be sited offshore which may reduce conflicts with other marine uses.	• High cost of technology installation compared to conventional energy supply. • Remoteness of some offshore sites may increase operating expenses. • Higher-energy sites may not be ideal/suitable for certain types of aquaculture systems. • Technology is still in the early stages of development.
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 or provide nutrients. • Infrastructure could be used to implement feeding systems and other aquaculture components that require platforms.	• High cost of technology installation compared to conventional energy supply. • Only suitable in tropical and subtropical regions. • Technology has been deployed in a few locations but is still in the early stages of development despite initial development decades ago.
Salinity Gradient	• Resource predictability and year-round power scheduling with a high degree of accuracy. • Suitable for nearshore areas. • Can provide access to freshwater, saltwater, and brackish water. • Baseload power is theoretically possible.	• High cost of technology installation compared to conventional energy supply. • Low power availability with current technology. • Technology is still in the early stages of development. • Limited suitable locations.

Once a marine energy technology type is selected, a specific device must be chosen. Archetypes of wave energy converters and tidal energy devices both vary widely; **Figure 5** shows several types of devices, but many more archetypes have been seen to date. Marine energy device selection is influenced by the energy resource characteristics (e.g., the tidal velocity profile for tidal energy and the dominant wave heights and periods for wave energy), site bathymetry, and the technical readiness and performance of potential devices. The performance of devices may be considered in terms of device capacity factor, efficiency, or cost of energy[11]. While there is currently no standard framework to compare between and select wave or tidal energy devices, project design considerations that should influence marine energy device selection can be identified.

Some of these design considerations are elaborated below for **wave** energy devices:

- Water depth should be considered. Shallow, nearshore water may be more suitable for single-body point absorber, overtopping, oscillating water column, wave surge, and submerged pressure differential devices. In deeper water where larger waves are found, two-body point absorbers and attenuators may be better-suited; however, most wave energy devices can be placed in either nearshore or deep waters.
- Devices must be able to withstand seasonal conditions (e.g., weather, sea state, ice) at the site.
- The scale of the device and its power output must be considered, as larger wave energy converters typically produce higher peak power and can be placed in more energetic wave states that occur farther offshore. Smaller wave energy converters may be more efficient in less energetic wave states. Wave energy devices can be expected to produce power on the order of tens of watts for smaller prototype-scale devices or up to hundreds of kilowatts or even one to two megawatts for larger devices.
- Wave energy devices can be tuned to a location's particular wave state[12] by adjusting the mechanical parameters of the system.
- The cost of the device and associated infrastructure, technology readiness level[13], existing supply chain, fabrication and assembly, and the device developer's level of experience, including previous successful deployments, should also be considered in selecting a device.

Design considerations for **tidal** energy devices are elaborated below:

- The tidal resource available indicates which types of device are possible. Axial and cross-flow turbines require water current speeds of 1-1.5 m/s to physically begin operation, but peak site current speeds often must reach at least 2.5 m/s for a turbine to be practical. Tidal

[11] Trueworthy et al. (in prep). A Responsive Research Agenda to Inform Community Decision Making in Wave Energy. *Link to publication and journal information will be included when available.*
[12] Guachamin-Acero & Portilla-Yandun. (2023). Tuning Wave Energy Converters to local wave conditions. Paper presented at 15th European Wave and Tidal Energy Conference (EWTEC 2023), Bilbao, Spain. https://doi.org/10.36688/ewtec-2023-176
[13] Snowberg et al. (2024). Marine Energy Technology Development Risk Management Framework. Golden, CO: National Laboratory of the Rockies. NLR/TP-5000-90212, p. 5 https://docs.nlr.gov/docs/fy24osti/90212.pdf

kites are able to operate in slightly lower velocities (1-3 m/s). Vortex-induced vibration devices can produce smaller amounts of power in water velocities as low as 0.25 m/s.

- The tidal energy device must be able to operate in bidirectional flow as the tide ebbs and flows. Cross-flow turbines are bidirectional. Axial flow turbines require a yawing mechanism to turn the turbine into flow as tides move in and out.
- Several locations in the water column are possible. For higher flows near the surface, a platform- or buoy-mounted device may be appropriate. For harvesting flows near the bottom or mid-water column, and for applications that must avoid surface vessel navigation, a bottom-mounted device may be appropriate (on piles, a lander, gravity anchors, etc.). Depth of water, tidal velocity profile, substrate type, and end-use of power can influence this design decision.
- The level of needed power influences device selection as well. Tidal turbines and kites can produce hundreds of watts to even one to two megawatts of power (influenced by device size. Meanwhile, vortex-induced vibration devices generate power on the scale of milliwatts to watts.
- The cost of the device, size, technology readiness level, existing supply chain, fabrication and assembly, and the developer's level of experience, including previous successful deployments, should also be considered in selecting a device.

Another component of defining a potential project includes identifying the appropriate consenting or regulatory regime that will be authorizing use (see 5. Navigate Regulatory Regime). This includes the overall process for siting, authorization, construction, and operation; important considerations for the project to document or assess (e.g., water quality parameters, protected or sensitive habitats or species that may be affected and trigger regulatory consultations, overlap with existing uses such as navigation and fishing, or lease requirements); and government agencies and key entities (Tribes, organizations, etc.) to coordinate or communicate with. This information will help in later steps as a project goes through regulatory processes. While navigating the regulatory regime is the final key consideration described in the Guide, the process needs to begin in these earlier steps with coordination and communication to enable a successful project (see also Understand Perspectives).

Define Potential Project: Checklist

- ☐ Determine the energy requirements of the aquaculture system. This may require conducting an energy audit.
- ☐ For aquaculture operators: Explore potential marine energy technologies. Consider the following aspects:
  - Wave or tidal resources available on site / nearby
  - Possible device types or mechanisms for harnessing energy (see **Figure 5**)
  - Size or power output based on energy requirements and resource availability
- ☐ For aquaculture operators: Identify specific marine energy devices and developers with which to collaborate on a potential project. Contact developers to initiate co-location conversations.

  OR

  For marine energy developers: Identify potential aquaculture companies or operation types in your areas of interest with which to collaborate on a potential project. Contact aquaculture operators to initiate co-location conversations.
- ☐ Collaboratively discuss the potential project, design considerations, and compatibility. The marine energy developer is best suited to answer questions about their specific device, possible configurations, and applications at a particular location. The aquaculture operator is best suited to answer questions about their species needs, power requirements, and other operability needs.
- ☐ Begin to identify regulatory considerations. Keep these in mind as the project is defined – see **5. Navigate Regulatory Regime** for full details.

2. Identify Key Attributes

Key attributes are the characteristics of the environment, aquaculture system, or marine energy technology that need to be identified at the beginning of a co-location project. A framework for co-locating aquaculture and marine energy was developed to help consider, evaluate, and prioritize goals, objectives, and key attributes for co-location (see **Figure 6**). This framework can help aquaculture operators and marine energy developers assess how key attributes align for both industry partners. The framework uses a multi-criteria decision-making approach which is a method for evaluating a variety of criteria and objectives to aid decision-making in complex systems. It focuses on key environmental, regulatory, and logistical parameters to inform spatial analyses to aid identification of suitable areas for co-location. The framework can be used to help align goals between aquaculture and marine energy needs; prioritize goals, objectives, and attributes which can then be ranked; and/or assign weights to each to aid systematic decision making. Based on the goal selected, the user can identify key attributes to minimize, maximize, or optimize the specific objectives. For example, as shown in **Figure 6**, if the goal is to reduce economic costs, the project will need to optimize aquaculture operations – considering lifetime cost of energy, supply chain, proximity to ports, proximity to hatcheries, and workforce in project development. Once the key attributes of the co-location project are identified, suitable areas can be explored (see 3. Find Suitable Areas).

Identify Key Attributes: Checklist

- ☐ Identify goals for co-location.
- ☐ Select objectives to minimize, maximize, or optimize to achieve each goal.
- ☐ Build a list of key attributes to consider in siting and designing a co-location project.

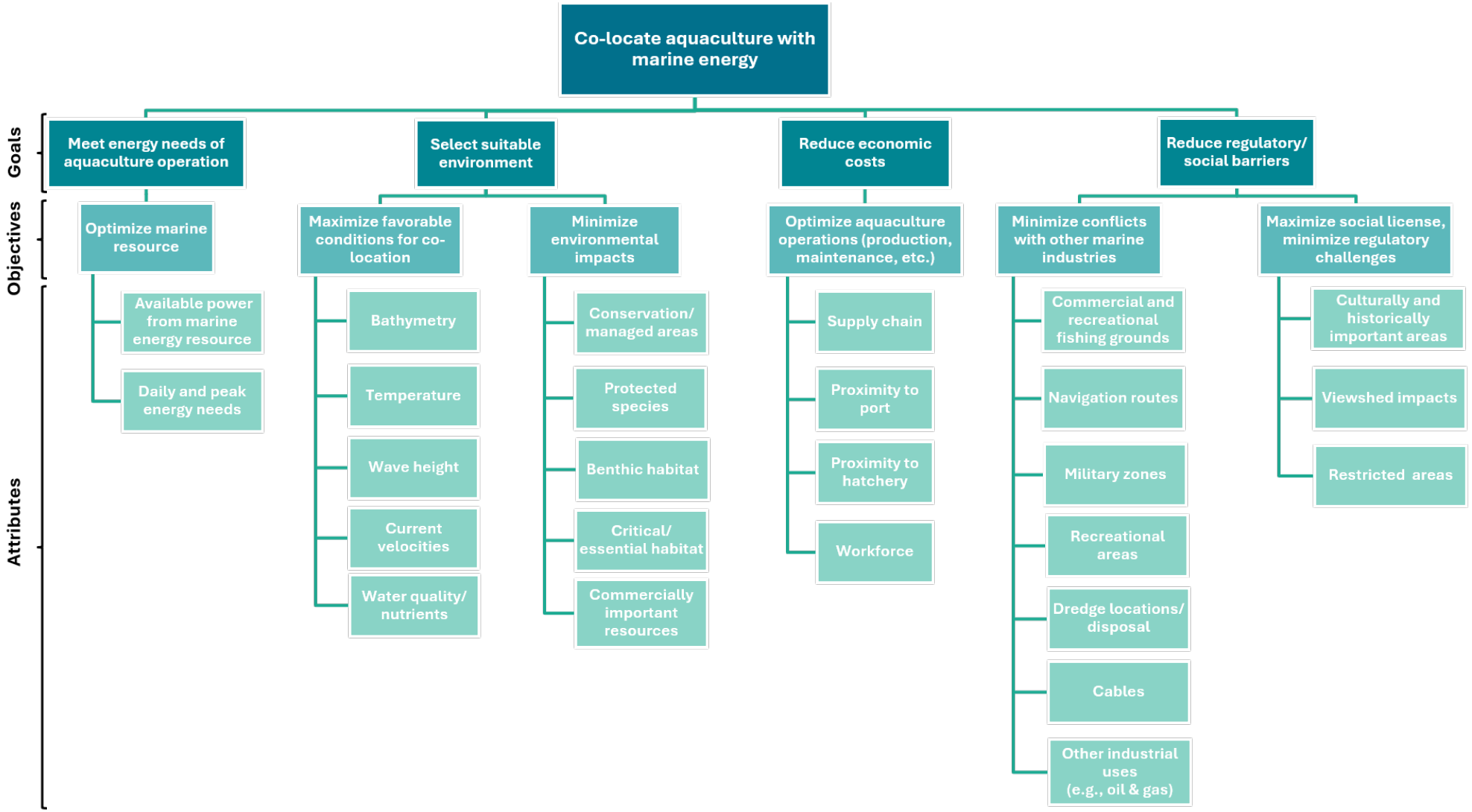


Figure 6. Framework for assessing co-location of aquaculture and marine energy using a multi-criteria decision tree with example goals, objectives, and attributes. When applied to a spatial analysis, weights can be added for each attribute to reflect suitability. See Garavelli et al. 2022[15] and Garavelli et al. 2025[16] for examples applying the framework.

3. Find Suitable Areas

Finding suitable areas to co-locate marine energy and aquaculture is another key step in assessing feasibility. This is particularly important because historically, aquaculture operations are sited in sheltered coastal waters where the cultivated species grow best but which are likely not viable for marine energy due to lower waves and slower currents. However, with offshore or exposed[14] aquaculture, the industry is moving into high-energy environments that may be suitable for marine energy. Additionally, a range of new marine energy technologies are being developed to harness energy in lower energy areas nearshore, or there may be suitable energy resources nearby aquaculture facilities even if not onsite that could function as charging stations or deliver power via cable.

Building on the key attributes detailed in 2. Identify Key Attributes and leveraging resources described in **Table 2**, suitable areas where both activities can optimally function with minimal conflict can be identified. The framework (**Figure 6**) can help define priority attributes for co-location depending on the goals and objectives of the project. For example, Garavelli et al. (2022)[15] identified suitable locations for co-locating wave energy and offshore aquaculture in the US through spatial analysis. Garavelli et al. (2025)[16] conducted a similar analysis specifically for Puerto Rico. In both studies, the key attributes to consider for co-location are defined and their associated constraints (e.g., depth range, wave height range, etc.) are detailed, with weights added to aid in the selection of suitable sites. For these studies, National Oceanic and Atmospheric Administration's (NOAA) Aquaculture Opportunity Areas Atlases (Morris et al. 2021[17]; Riley et al. 2021[18]) methods and weights were consulted and where possible aligned.

Once suitable areas have been identified, a specific site needs to be selected. From a technical perspective, additional site-specific characteristics can be obtained through environmental assessments or feasibility studies to supplement desktop analyses. This may include validation of the information on each attribute as well as any other location-specific conditions, such as regulatory requirements or community perspectives.

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[14] Buck et al. (2024). Resolving the term "offshore aquaculture" by decoupling "exposed" and "distance from the coast." *Frontiers in Aquaculture*, https://doi.org/10.3389/faquc.2024.1428056

[15] Garavelli et al. (2022). A feasibility assessment for co-locating and powering offshore aquaculture with wave energy in the United States. *Ocean and Coastal Management,* https://doi.org/10.1016/j.ocecoaman.2022.106242

[16] Garavelli et al. (2025). Suitability for co-location of offshore aquaculture and wave energy in the US Caribbean. *Environmental Research Letters,* http://doi.org/10.1088/1748-9326/ae0805

[17] Morris et al. (2021). An Aquaculture Opportunity Area Atlas for the Southern California Bight, NOAA Technical Memorandum NOS NCOOS 298. https://doi.org/10.25923/TMX9-EX26

[18] Riley et al. (2021). An aquaculture opportunity area atlas for the U.S. Gulf of Mexico. NOAA Technical Memorandum NOS NCCOS 299. https://doi.org/10.25923/8cb3-3r66

Table 2. Sample spatial data resources for suitability analysis. Many additional resources exist at the regional and state levels. Acronyms included in the table: Bureau of Ocean Energy Management (BOEM), National Oceanic and Atmospheric Administration (NOAA), National Centers for Coastal Ocean Science (NCCOS), National Laboratory of the Rockies (NLR), U. S. Fish and Wildlife Service (USFWS), U.S. Army Corps of Engineers (USACE), U.S. Geological Survey (USGS).

Resource Name and Organization	Types of Spatial Data Available	Link
Marine Energy Atlas (NLR)	Marine energy resource data (wave, tidal, currents), environmental layers, infrastructure, and use constraints	https://maps.nlr.gov/marine-energy-atlas
Aquaculture Opportunity Areas (NOAA)	Programmatic environmental impact statements for various regions of the U.S. Several regional Atlases are available that include more than 200 data layers on environmental, economic, social and cultural considerations.	https://www.fisheries.noaa.gov/national/aquaculture/aquaculture-opportunity-areas Alaska Atlas: https://doi.org/10.25923/nxhb-vt48 Gulf of America Atlas: https://doi.org/10.25923/8cb3-3r66%20 Southern California Atlas: https://doi.org/10.25923/tmx9-ex26
Marine Cadastre (BOEM)	Offshore energy leases, submarine cables, pipelines, shipping lanes, fishing activity, bathymetry, habitat, administrative boundaries (300+ GIS layers)	https://marinecadastre.gov
OceanReports (BOEM/NOAA)	Generates reports based on selected spatial area that includes energy information, natural resources, oceanographic and biophysical information, transportation and infrastructure, and economic layers	https://marinecadastre.gov/oceanreports/
National AquaMapper (NOAA – NCCOS)	Aquaculture opportunity areas, oil and gas leases, military areas, shipping lanes, submarine cables, vessel traffic, bathymetry, biologically important areas, water quality and chemical composition	https://www.arcgis.com/apps/webappviewer/index.html
Renewable Energy GIS Data (BOEM)	Marine energy planning areas, lease blocks, constraints, environmental studies, infrastructure proximity	https://www.boem.gov/renewable-energy/mapping-and-data
Fisheries GIS (NOAA)	Essential Fish Habitat, protected species, fisheries closures, critical habitats, ecosystem sensitivity layers	https://maps.fisheries.noaa.gov/portal/apps/mapviewer/index.html

Marine Geospatial Ecology Tool (NOAA – NCCOS)	Habitat suitability modelling, species distribution models, sea surface temperature, salinity, aquaculture siting tools	https://coast.noaa.gov/digitalcoast/tools/mget.html
Integrated Ocean Observing System (NOAA)	Real-time and historical oceanographic data: waves, currents, temperature, water levels	https://ioos.noaa.gov
Marine Spatial Planning Data: U.S. Caribbean (NOAA-NCCOS)	Spatial datasets for Puerto Rico and U.S. Virgin Islands: aquaculture suitability, conservation priorities, human use conflicts	https://coastalscience.noaa.gov/project/marine-spatial-planning-data-development-u-s-caribbean/
National Data Buoy Center (NOAA)	Wave height, wind speed, currents, meteorological time-series for engineering and aquaculture conditions	https://www.ndbc.noaa.gov
Critical Habitat and Species Data (USFWS)	Endangered species distributions, critical habitat designations, migratory bird data	https://ecos.fws.gov/ecp/
Coastal and Marine Geology Data System (USGS)	Seafloor mapping, bathymetry, sediment type, benthic habitat, geohazards	https://cmgds.marine.usgs.gov
Geospatial Open Data (USACE)	Navigation channels, dredging areas, permitted structures, regulatory boundaries affecting siting	https://geospatial-usace.opendata.arcgis.com/

Find Suitable Areas: Checklist

- ☐ Determine scope of suitable area analysis. In the case where an aquaculture operation is already established (e.g., leases obtained or some existing access plans), less exploration is necessary.
- ☐ Use the resources in **Table 2** to locate potential data sources.
- ☐ If analysis is high level and exploratory, consider assigning weights to key attributes and conducting a spatial analysis to identify potential regions of interest (see Garavelli et al. 2022; 2025).
- ☐ Select a site for the co-location project based on suitable areas. This will likely further require:
  - Regulatory considerations
  - Access or lease considerations for use of the area
  - Community input and public meetings

Case Study: Finding Suitable Areas for Nearshore Co-Location

As part of a research project to explore opportunities for nearshore aquaculture and marine energy co-location, Branch et al. *in prep* examined the overlap of tidal energy resources and existing shellfish farms, identified using existing leases held in state aquaculture permitting databases. Farms were mapped against the annual average tidal current speed acquired from the Marine Energy Atlas[19].

Farms in high energy areas were identified and contacted to assess interest in collaborating on research to measure the actual current speeds on site at farm operations. This resulted in the selection of three farms for micro-siting surveys to collect field measurements: Ferda Farms (New Brunswick, Maine), Hog Island Oyster Company (Humboldt Bay, California), and Taylor Shellfish (Puget Sound, Washington).

The three farms were visited by PNNL researchers to assist in the deployment and recovery of an acoustic doppler current profiler (ADCP) at several sites for each farm. Researchers also interviewed the farm staff about their operations and power needs, with emphasis on off-grid or on-water power needs that would be most suited to marine energy. From this collaboration, the maximum and average current speeds were measured at each farm site and power curves were generated to estimate the amount of power that could be generated at each site.

The strongest currents were measured at Hog Island Oyster Company, reaching 1.68 m/s, which is sufficient to power a typical tidal turbine. However, with the early stage of marine energy technologies, installing any marine energy device would not likely reduce costs, so the motivation for such a project would need to go beyond economic considerations. The current speeds measured at Ferda Farms and Taylor Shellfish sites were not high enough for standard tidal turbines, though they may be high enough for some lower-speed technologies, such as those using vortex induced vibration energy or tidal kites. The two farms with lower marine energy resources appear to have nearby locations that have higher currents based on observations at site visits – though this would need to be further validated, and considerations around power transport (cable or battery charging) would need to be understood. These farms both have significant off-grid or on-water power uses that could benefit from marine energy.

The shellfish farm case studies indicate that while tidal energy can support electricity generation at some sites, its availability is highly site-specific and may not coincide with the off-grid or on-water power requirements of the farms. In finding suitable areas, it is important to consider the site-specific power needs at a high resolution, as well as go beyond modeling to understand the available marine energy resources and move toward a successful project.

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[19] National Laboratory of the Rockies. (2025). Marine Energy Atlas. https://maps.nlr.gov/marine-energy-atlas/. Data used is Tidal Current Speed Layer, from Haas et al. 2011. “Assessment of Energy Production Potential from Tidal Streams in the United States”. United States. https://doi.org/10.2172/1219367

4. Integrate Systems

Physical and electrical integration of marine energy devices and aquaculture systems is a key knowledge gap for co-location. 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 systems, and the proximity of other on-water infrastructure. The variety of aquaculture systems and marine 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 marine energy systems will require each to function on their own, while being thoughtfully integrated. For example, minimizing downtime and maintenance of the marine energy system is essential, as aquaculture farms operate daily, and certain cultivated species, such as fish, require continuous monitoring. Any unexpected interruption to power supply could have a serious impact on aquaculture operations. Therefore, marine energy systems powering aquaculture need to be reliable and may need a suitable backup or storage system in place. To advance understanding of integration, there is a need to assess potential options for integration and work towards pilot or demonstration projects.

Given the nascency of co-location, high variability in conditions both aquaculture and marine energy systems, and continued unknowns, strong communication and clear agreements between all parties involved is critical to ensure the safest and most effective collaboration. Opportunities for integration should be further explored to detail if and when aquaculture and marine energy systems can be integrated into a singular shared physical structure or if there is a need to have separate but electrically connected systems. PNNL is currently undertaking research to explore this question. Additionally, Davonski (2024)[20] provides some insight into this topic, specifically for an integrated multi-trophic offshore aquaculture system with wave energy.

Integrate Systems: Checklist

- ☐ Discuss physical, electrical, and mechanical systems integration in collaboration with marine energy developer and aquaculture operator.
- ☐ Identify any additional testing to complete before installation.
- ☐ Identify any needs and/or sizing for battery storage.
- ☐ Plan for backup power in the event of system failure.

[20] Davonski, Z. (2024). Considerations for a Co-located Aquaculture and Wave Energy Deployment: Quantifying Demand and Assessing Integration (Report No. PNNL-36863). Report by Manna Fish Farms, Inc. Report for Pacific Northwest National Laboratory (PNNL). https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-36863.pdf

5. Navigate Regulatory Regime

The regulatory context and associated permitting processes to develop any project at sea are complex. In the case of a co-located project for marine energy and aquaculture, as a novel application, there are not yet specific integrated permitting processes to follow or guidance available. However, there are existing regulatory regimes which are likely to apply to marine energy and aquaculture activities.

To bring together the two industries, two options exist for planning purposes: planning from the start versus adding marine energy to an existing aquaculture operation. This Guide describes existing resources for navigating the regulatory processes for marine energy and aquaculture, separately. So far, it is unknown how permitting would change in the case of a co-located project though it is likely that both permitting processes would need to be undertaken in parallel.

To highlight some examples, the following tables[21] describe regulatory processes of aquaculture and marine energy in the US. For both, the location of the project in federal versus state waters significantly impacts the process, and regulatory processes at multiple levels of jurisdiction will likely need to be considered. A case study on permitting marine energy and aquaculture in Puerto Rico is also included.

Navigate Regulatory Regime: Checklist

- ☐ Review the resources in the tables below to identify regulatory requirements for the aquaculture operation and marine energy system.
- ☐ Contact your Regional Aquaculture Coordinator for guidance.
- ☐ Identify additional data that needs to be collected in preparing for regulatory requirements.
- ☐ Map out timelines for permitting and regulatory activities.

[21] Tables were last updated in April 2026, though new information and resources are regularly made available and requirements may change. Contact your Regional Aquaculture Coordinator or local regulator for the most accurate information.

Aquaculture

Federal Guidance

- NOAA Fisheries Guide to Permitting Marine Aquaculture in the United States (2022). This document aims to help the aquaculture industry navigate federal permitting process for commercial marine aquaculture (finfish, shellfish, invertebrates, seaweed) as it describes federal regulatory requirements and relevant federal and state agencies involved in permitting and operations. It provides additional detail on the information provided in this table organized by sections on: Federal Authorizations, Overview of Federal Permitting Process, Other Federal Agency Authorizations and Processes, Federal Consultation and Review Requirements, Regulations Applying Directly to Operators of Aquaculture Facilities, and a Summary of Federal Agencies Involved in Aquaculture Permitting and Authorizations.
- Marine spatial planning and best siting practices to achieve an ecosystem approach to aquaculture in the United States (NOAA 2025)
- **Water quality/environment:** Clean Water Act National Pollution Discharge Elimination System (NPDES) permit (U.S. Environmental Protection Agency (EPA) or authorized state agency), Clean Water Act 404 permit and/or verification (U.S. Army Corps of Engineers [USACE]), Magnuson-Stevens Fisheries Conservation and Management Act (MSA) permits (National Marine Fisheries Service [NMFS]).
- **Construction:** Rivers and Harbors Act Section 10 permit and/or verification (USACE), U.S. Coast Guard [USCG] Private Aids to Navigation).
- **Consultation:** Endangered Species Act (ESA) Section 7 (NMFS, U.S. Fish and Wildlife Service [FWS]), Essential Fish Habitat (EFH) under the MSA (NMFS), National Environmental Policy Act (NEPA) Environmental Impact Assessment or Environmental Assessment if not Categorical Exclusion (EPA, designated federal agency), Marine Mammal Protection Act (MMPA) (NMFS, FWS), Fish and Wildlife Coordination Act (FWCA) (FWS), National Historic Preservation Act (NHPA) Section 106 (Advisory Council on Historic Preservation [ACHP]), Coastal Zone Management Act (CZMA) (designated state agency), National Aquaculture Health Plan and Standards (U.S. Food and Drug Administration [FDA]), National Marine Sanctuary Act (NMSA) (NOAA).
    - If co-located with existing oil and gas facilities the Marine Minerals Administration (MMA)* reviews and provides certain approvals for activities permitted by EPA and USACE.
    - Some projects may require consultation with the U.S. Department of Defense's Military Aviation and Installation Assurance Siting Clearinghouse.
- **Permitting agencies:** USACE, EPA, and NMFS (for certain activities, in all areas except the Gulf of America).
- **Authorizing agencies:** MMA, NMFS, USCG, FWS, FDA.
- NOAA has Regional Aquaculture Coordinators assigned that can be helpful references.
- Federal agencies have been setting up **regional coordination groups** for efficient/streamlined regulatory process in some regions (e.g., offshore aquaculture in the Southeast).
- NOAA has also identified Aquaculture Opportunity Areas (AOAs) to support comprehensive site selection for sustainable offshore aquaculture that minimizes impacts, reduces conflicts, and considers environmental, economic, and social aspects. This process ends with the completion of a Final Programmatic Environmental Impact Statement (PEIS) for the AOAs considered and issuance of a decision. The PEISs may help create efficiencies in the permitting and environmental review processes for aquaculture operations that may be proposed within designated AOAs in the future. However, it is important to note that these PEISs do not consider potential effects of co-location with marine energy.

Regional Guidance	• NOAA guide for Gulf of Mexico (2019) and for Pacific Islands (2024), Best Management Practices in the Caribbean (2014), West Coast Guidance (2025). • New England Fishery Management Council's report on Aquaculture in the New England Region (2021).
State Guidance	• Projects located in state waters will also require consideration of state and potentially county- or municipal-level regulations. These regulations, the species considered, and the agencies involved vary widely. • NOAA State by State Guidance for seaweed, finfish, and shellfish (2021). • National Sea Grant: State Marine Aquaculture Policy Dashboard (2023) • Alabama: Alabama Oyster Permit Application Guide (2025); Alabama Marine Resources Division Shellfish Aquaculture Siting Tool • Alaska: Alaska Aquaculture Permitting Guide (2021) • California: State Permit Guide to Aquaculture in California (2025); NOAA Guide to Leasing, Permitting and Authorizing Commercial Aquaculture Operations off the California Coast (2025); Greenwave Guide to Navigating Lease & Permit Approvals for Ocean Farming in California (2018); Greenwave Guide to Leasing & Permitting for Bull Kelp Farming and Restoration Projects in California Using Suspended Longline Gear (2024) • Connecticut: Guide to Marine Aquaculture Permitting in Connecticut (2024) • Florida: Florida Department of Agriculture and Consumer Services - Aquaculture Certificate of Registration; Aquaculture Best Management Practices Manual (2023) • Georgia: Georgia Aquaculture Regulations & Licensing • Louisiana: Louisiana Wildlife and Fisheries - Alternative Oyster Aquaculture • Massachusetts: Massachusetts Permitting Tool • Mississippi: Mississippi Department of Agriculture and Commerce - Aquaculture • New Jersey: New Jersey Permitting Guidance Documents (2022) • New York: A Guide to Shellfish Aquaculture Permitting in New York (2022) • Oregon: Guide to Shellfish Aquaculture Permits in Oregon (2025) • South Carolina: Sea Grant South Carolina Aquaculture Permitting Guide (2021) • Texas: Texas Sea Grant – Oyster Mariculture Permitting Process Overview • Virginia: Virginia Sea Grant – Shellfish Aquaculture in Virginia • Washington: Guide to Shellfish Aquaculture Permits in Washington (2025); Guidance for Commercial Marine Finfish Net Pen Aquaculture (2022)

*Previously Bureau of Ocean Energy Management (BOEM)/Bureau of Safety and Environmental Enforcement (BSEE)

Marine Energy

Federal and State Guidance

- Handbook of Marine Hydrokinetic Regulatory Processes (2020): This document is meant to help stakeholders access and understand federal and state authorization processes. It outlines federal and state regulatory requirements, describes relevant processes, and identifies federal and state agencies involved. It also highlights federal and state authorizations for states where marine energy development is taking place or likely to occur (Alaska, California, Florida, Hawaii, Maine, Massachusetts, Oregon, Rhode Island, Washington).
- **Authorizations:** Preliminary permit (Federal Energy Regulatory Commission [FERC]), FERC license (Integrated Licensing Process - default, Traditional Licensing Process, Alternative Licensing Process; pilot project or Verdant Exception – not required if not grid connected), and BOEM lease, Nationwide Permit 52 (USACE), CWA Section 404 permit (USACE), Rivers and Harbors Act Section 10 permit (USACE), NEPA analysis (including categorical exclusion; FERC), and others (e.g., Private Aids to Navigation - USCG).
- **Consultation:** ESA Section 7 (NMFS, FWS), MMPA (NMFS, FWS), EFH Assessment (NMFS), FWCA Consultation (FWS), Migratory Bird Consultation (FWS), NHPA Section 106 (ACHP), CZMA (designated state agency), Water Quality Certification (CWA Section 401; designated state agency).
- Additional information on environmental regulatory requirements for marine energy in the United States is available in OES-Environmental's **Country Specific Guidance Document**.

Case Study: Navigating the Regulatory Regime in Puerto Rico

Co-location of offshore aquaculture and wave energy around Puerto Rico was explored by Garavelli et al. 2025[22]. There are no comprehensive permitting processes for aquaculture or marine energy in the territorial waters of Puerto Rico[23]. Currently, environmental reviews of marine aquaculture permits in the U.S. Caribbean are addressed on a case-by-case basis. The Joint Permit Application (Federal and Commonwealth Joint Permit Application for Water Resource Alterations in Waters, including Wetlands of Puerto Rico) is a consolidated process that would likely be used to request relevant permits from the Puerto Rico Department of Natural and Environmental Resources (DNER), USACE, Puerto Rico Planning Board, and the Environmental Quality Board. Permit applications are submitted to DNER, who as the proponent agency is required to submit and process the application. DNER also requires structures using territorial waters or submerged lands to obtain an Authorization of a Concession (essentially a lease) for an annual fee, which includes the requirement for a public notice filing. Consultation is carried out with the Underwater Archaeology, the Puerto Rico State Historic Preservation Office, and the Ports Authority to endorse the proposed project if no conflicts are determined. A Coastal Zone Federal Consistency Certification is required in the case of a federal project or impacts to marine resources. The capture, import, and/or export of aquaculture organisms requires a special permit from the Secretary of DNER. When DNER considers it necessary, a public responsibility insurance policy and/or Environmental Impact Statement may be required.

Within Puerto Rico, the main challenge to have a designated permitting process for aquaculture seems to be a lack of industry investment and therefore no impetus for the Puerto Rico government to develop a comprehensive permitting process or strategy for aquaculture. If aquaculture development increases, the Coastal Zone Management Program and DNER would have "a clear role in working with [other agencies and stakeholders] to design and develop aquaculture policies, siting plans, operational procedures", such as suitability analyses and mapping for siting (Puerto Rico §309 Assessment & Strategy 2026-30[24]). There are several agencies in Puerto Rico with interest or involvement in aiding aquaculture. The Puerto Rico Department of Agriculture is charged with promoting aquaculture and is leading an aquaculture initiative to expand activities in the Commonwealth to take pressure off coral reef fishing impacts. The Coastal Zone Management Program will monitor and provide support to pilot aquaculture projects, specifically those that incorporate working waterfronts redevelopment and aquaculture, and the Department of Commerce Economic Development Administration may be involved in supporting or funding early aquaculture operations. Recently, The Nature Conservancy published a report[23] reviewing marine aquaculture and permitting processes to identify solutions and pathways forward.

Aside from ocean thermal energy conversion, to our knowledge, there have been no proposals for marine energy projects in Puerto Rico. This likely explains the absence of established permitting processes for marine energy beyond a broad energy policy framework (Puerto Rico Energy Public Policy Act 2019[25]). While "at-sea applications for marine energy" is identified as a possible enhancement area under Section 309 of the CZMA, a 2021

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[22] Garavelli et al. (2025). Suitability for co-location of offshore aquaculture and wave energy in the US Caribbean. *Environmental Research Letters* 20(10): 104071. https://doi.org/10.1088/1748-9326/ae0805

[23] The Nature Conservancy. (2026). Marine aquaculture policies and regulations in Puerto Rico. https://www.aquaculturescience.org/content/dam/tnc/nature/en/documents/aquaculture/PRCaseStudyEnglishl.pdf

[24] Puerto Rico Department of Natural and Environmental Resources (2026). Final Section 309 Assessment and Strategy 2026 to 2030. https://www.drna.pr.gov/wp-content/uploads/2026/03/Final-Section-309-PRCZMP-FY26-30.pdf

[25] Puerto Rico Energy Public Policy Act. Act No. 17 of April 11, 2019 and amended March 19, 2025. https://bvirtualogp.pr.gov/ogp/Bvirtual/leyesreferencia/PDF/2-ingles/17-2019.pdf

Understand Perspectives

Throughout project development, it is necessary to consider stakeholder, rightsholder, and community perspectives. Ideally, any project should include community members from the outset, understanding their values and contexts so that a co-located project can maximize benefits to a community and minimize negative impacts (Rose and Freeman 2024[26]).

A few key findings from engagement efforts carried out around PNNL's co-location research over the last few years highlight the need for:

- Assessing feasibility for co-location comprehensively, including considerations beyond only aquaculture and marine energy, such as social, cultural, and economic effects, supply chain, workforce, jobs, education, environmental effects, potential conflicts with existing users, and more. This also requires balancing various perspectives and needs (e.g., community/local, technical, business, environment).
- Understanding 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.
- Prioritizing engagement with Tribes, stakeholders, and local communities, especially fishing communities and other sea users, and learning from them and incorporating their perspectives. Additionally, exploring synergies such as fishing or tourism around co-location and potential benefits like food and energy security.
- Incorporating location-specific needs and challenges as part of feasibility assessments, and applying community-led, participatory approaches[27] with transparent communication. Ideally, this includes having co-location projects led by communities and/or locally based businesses.
- Addressing concerns around environmental effects of both marine energy and aquaculture, including cumulative effects.
- Testing technologies and co-location integration through pilot or demonstration projects in a research setting before bringing a co-located project to communities will be important to build trust and have support. It may be of interest for communities to have co-located aquaculture and marine energy systems that are proven from a technology perspective, are reliable, and can be easily integrated before being deployed.

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[26] Rose, D. and Freeman, M. (2024). Stakeholder Engagement for Marine Renewable Energy. 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. https://tethys.pnnl.gov/publications/2024-state-science-report-chapter-5-stakeholder-engagement-marine-renewable-energy

[27] Example participatory approaches could include workshops, group discussion, participatory mapping, scenario planning, structured interviews, ethnographic research.

Remaining Research Needs

While progress has been made to work towards co-located aquaculture and marine energy deployments, there are remaining knowledge gaps to be filled through research and ultimately implementation of co-location projects. These include:

- Understanding energy needs of aquaculture operations, particularly of various aquaculture systems, as energy use varies widely,
- Demonstrating the physical integration of aquaculture and marine energy system infrastructure,
- Testing existing permitting processes for co-located projects,
- Elucidating unknowns regarding insurance and liability,
- Understanding environmental effects, including cumulative and interaction effects between systems,
- Optimizing efforts to proactively identify and evaluate locations that minimize environmental effects and conflicts with existing uses, and
- Analyzing potential costs and/or cost-savings from co-location.

For more information on PNNL's work on marine energy and aquaculture, visit
https://www.pnnl.gov/projects/marine-energy-aquaculture

