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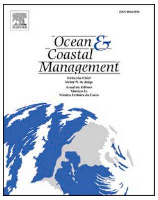

A feasibility assessment for co-locating and powering offshore aquaculture with wave energy in the United States

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ABSTRACT

Offshore aquaculture and marine renewable energy (energy from waves, tides, currents, and ocean gradients) are two developing ocean-based industries. Aquaculture, an industry that has typically relied on diesel for power, is expected to grow globally, presenting an opportunity to reduce greenhouse gas emissions by switching to renewable sources as it expands. As the aquaculture industry moves further offshore and is situated in more energetic environments, the prospect to co-locate offshore aquaculture with wave energy increases. To improve understanding of this potential, a feasibility assessment was completed to estimate the energy needs and wave resource required to power offshore finfish aquaculture operations. The study found it is possible to power offshore aquaculture operations entirely with wave energy. A spatial analysis was then performed to assess the suitability of co-locating offshore finfish aquaculture and wave energy off California and Hawaii. Suitable locations were identified offshore of O'ahu, Hawaii, and northern California. Southern California was also assessed, using a lower wave resource, based on study areas evaluated by the National Oceanic and Atmospheric Administration to identify Aquaculture Opportunity Areas, and while limited there are suitable locations that may warrant further evaluation. This study presents an analysis into the potential to pair wave energy with offshore aquaculture, and how various factors can help determine suitable areas for co-location. The methods developed in this study will support future identification of potential sites for development and decision-making to optimize the success of co-locating wave energy resources and offshore finfish aquaculture.

1. Introduction

Mitigating the effects of climate change, and therefore reducing greenhouse gas emissions calls for an increase in the use of renewable energy. Covering 70% of the world's surface, the ocean is a large source of renewable energy that can contribute to global decarbonization (United Nations General Assembly 2012). Marine renewable energy (MRE) is defined as energy generated from the movement of water (waves, tides, currents), as well as from salinity and temperature gradients (Ocean Energy Systems 2019). MRE is an emerging industry with large potential worldwide that can provide clean energy and reduce greenhouse gas emissions. While MRE has traditionally been thought of as bringing power to the grid, it can also deliver power at sea, especially to activities that are currently facing limitations based on using traditional sources of energy such as diesel (LiVecchi et al., 2019).

One of the ocean-based activities that can be powered by MRE is offshore aquaculture (LiVecchi et al., 2019). While aquaculture is not a new industry, it is exponentially developing worldwide as the demand to produce protein increases (Costello et al., 2020). Worldwide, the aquaculture production is expected to increase by 32% (26 million tonnes) in 2030 (Food and Agriculture Organization 2020). As aquaculture production grows, the industry is developing offshore to reduce nearshore environmental effects and competition for space (Di Trapani et al., 2014; Soto and Wurmann 2019; Food and Agriculture Organization 2020) and MRE innovation can help advance this sector. For example, the United States (US) is planning for expanded seafood production including offshore aquaculture development and is currently identifying aquaculture opportunity areas that can aid industry advancement (Executive Order 13921; Morris et al., 2021). As the aquaculture industry moves further from shore, it requires increased energy for transportation (Food and Agriculture Organization of the United Nations, 2015) resulting in an increase in costs to operators and

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carbon emissions. In addition, some offshore aquaculture operations are expected to greatly increase in size, adding to the energy requirements of the system (Menicou and Vassiliou 2010). Offsetting fuel use, carbon emissions, and energy needs by using MRE for on-site energy would benefit the growing offshore aquaculture sector and help limit the climate impact of its operations.

MRE is reliable and predictable, and water movement has a greater energy density than wind and solar, which can contribute to the expansion of offshore aquaculture in areas that are challenging for traditional energy resources (LiVecchi et al., 2019). Although offshore aquaculture is a promising market for the MRE industry, the assessment of energy-specific uses and demands is relatively scarce. While the potential to use wind and solar energy for powering offshore aquaculture has been explored (ABB 2019), using MRE as a power source has been minimally evaluated. Worldwide, there are few examples of offshore finfish aquaculture operations using renewable energy to power operations. Research projects have assessed the use of wave energy to power offshore finfish aquaculture in Scotland (Campbell 2017) and offshore seaweed aquaculture in Wales (MARIBE 2016). In China, an offshore finfish aquaculture operation is currently powered by both wave and solar energy (Ocean Energy Systems 2021; Ma et al., 2022).

The feasibility of integrating offshore aquaculture operations with other ocean uses has been assessed and may provide lessons learned for pairing MRE and aquaculture. Some examples include integrating oil and gas platforms with offshore aquaculture in the Gulf of Mexico and off California (Kaiser et al., 2010; Harmon 2016) or combining offshore wind farms and offshore aquaculture in Europe (Buck et al. 2008; Griffin et al., 2015; Jansen et al., 2016). A study based in the Canary Islands assessed the potential to co-develop aquaculture, wind, and wave energy, finding suitable areas for the development of aquaculture and wind farms but none for aquaculture and wave energy (Weiss et al., 2018). These studies found that offshore ocean platforms can provide an existing structure to develop offshore aquaculture. However, these did not look at powering aquaculture operations, which will require sources of energy generated on-site (Menicou and Vassiliou 2009) that could be provided by offshore wind or other sources such as wave energy. While wave energy does not provide a structure for aquaculture, wave devices can be incorporated with the aquaculture structure (attached to/sharing the aquaculture net pen moorings or anchors) or moored separately to provide power (e.g., connected through a feed barge).

There are potential challenges regarding powering offshore aquaculture with MRE. Coastal or nearshore aquaculture operations generally require less energetic wave climates, whereas larger wave climates are needed for energy production (Lehmann et al., 2017). Offshore aquaculture is likely to be in locations where the wave climate is more favorable for producing power and, by being further from shore, will demand power to be produced on-site. In addition, the wave industry is developing smaller-scale devices for off-grid applications that may be a viable solution for powering aquaculture in smaller wave climates (LiVecchi et al., 2019).

With the growing development of both MRE and aquaculture in offshore waters, the feasibility of pairing both industries needs to be evaluated. This study assessed the feasibility for co-locating offshore aquaculture operations with MRE, specifically wave energy, focusing on offshore finfish aquaculture in the US. In this study, co-location is defined as marine uses developed within the same space and time scales, and specifically focuses on integrating and powering aquaculture with wave energy, and offshore is defined as areas with depths of 25 m or more. Energy requirements and important factors for co-location were identified. A spatial analysis was then performed, guided by mapping modeled wave energy resources with other key parameters conducive to siting offshore aquaculture. Favorable areas for co-locating offshore aquaculture and wave energy were identified off California and Hawaii, followed by a localized assessment of suitability in each location. The analyses developed in this study will support future identification of potential sites for development and decision-making to optimize the success of co-locating wave energy resources and offshore finfish aquaculture.

Table 1
Parameters of interest and associated constraints used to identify favorable areas for co-locating offshore aquaculture and wave energy in the US, including sources of information and references for the constraint.

Category	Parameter	Source	Constraint	Reference
Environmental	Bathymetry	NOAA Coastal Relief Model	25–100 m	SARF (2014); Kapetsky et al. (2013)
	Wave height	US Department of Energy Marine Energy Atlas	0–2.5 m	SARF (2014)
	Wave power density	US Department of Energy Marine Energy Atlas	20–40 kW/m	Møller (2019)
	Current velocities	Hydrodynamic model HYCOM	0–1 m/s	Kapetsky et al. (2013); Klinger et al. (2017)
Regulatory	Managed areas	NOAA Marine Protected Areas Inventory	Exclusion of area	Lester et al. (2018a)
Logistical	Navigation routes	Marine Cadastre (2017 Vessel Transit Counts)	Exclusion of area	Alvarado et al. (2016); Lester et al. (2018a)
	Ports	NOAA Office for Coastal Management	0–60 km	Kapetsky et al. (2013)

NOAA = National Oceanic and Atmospheric Administration.
HYCOM = Hybrid Coordinate Ocean Model.

2. Materials and methods

This study consisted of two interrelated efforts: (1) an assessment of offshore aquaculture to determine the overall energy needs for operation, and (2) a spatial analysis to identify locations viable for both offshore aquaculture and wave energy production in the US. Semi-structured remote, video stakeholder interviews were conducted with five US aquaculture experts throughout the project to inform the energy assessment and spatial analyses, and to provide relevant information about US offshore aquaculture operations.

2.1. Offshore aquaculture energy assessment

To understand the on-site, non-transportation energy requirements for offshore aquaculture and estimate power needs from wave energy, a literature review was completed. The literature review included a search for relevant papers on offshore aquaculture and energy or electricity use, but also included papers on nearshore aquaculture. Studies on energy used and electricity consumption from aquaculture operations (nearshore and offshore) were reviewed. Citations from these studies were followed to verify data relevance and identify additional literature. While the offshore aquaculture market is nascent, particularly in the US where no offshore finfish aquaculture has been developed, certain overseas markets in Asia and Europe are further along and have industrial suppliers whose commercial products (e.g., feeding barges, net pens) are designed to meet the needs of these operations. A review of the energy-related specifications of the products currently available provided valuable data about the energy demands of these systems. Stakeholder interviews provided additional information to characterize energy use for offshore finfish aquaculture operations.

The assessment did not include energy for transportation, which was outside of the project scope but is an important consideration for fully understanding the energy use of aquaculture operations. Estimates of energy needs from the literature, confirmed by interviews, were used in the spatial analyses.

2.2. Spatial analysis

Two study locations were chosen to determine areas for co-locating offshore aquaculture with wave energy, based on the existence of current nearshore or coastal aquaculture, potential for offshore finfish aquaculture, and the availability of wave energy resources in US waters: offshore of California and Hawaii.

The study was completed in two stages, a regional assessment to identify favorable areas for co-location along the entire coasts of California and Hawaii (see Section 2.2.1 below for details), and a local assessment built on the identified favorable areas to provide a local analysis of suitability for co-location (see Section 2.2.2 below for details). Depths of 25 m or more were used to define offshore aquaculture, versus nearshore or coastal aquaculture operations (Lester et al., 2018a).

2.2.1. Regional assessment

Information on relevant environmental, regulatory, and logistical parameters of interest for co-location was gathered from the literature and stakeholder interviews (Table 1).

Environmental parameters included wave height, wave power, bathymetry, and current velocities, and their sources are described in Table 1. Modeled mean monthly values were obtained for wave power and wave height from 1980 to 2009 at a resolution of approximately 200 m along the shoreline out to 350 m. Modeled mean current velocities were obtained at a resolution of 1/12° (~9 km) and were available from April 2017 to March 2018. We assume no interannual variability in environmental conditions. To assess the seasonal variability of wave power, wave height, and current velocities, each dataset was split into two seasons – winter from October to March and summer from April to September – and averaged. Other environmental parameters such as oxygen or water temperature were not considered in this study as our analysis focused on general considerations for aquaculture and energy operations and was not specific to any fish species. Regulatory and logistical factors that might restrict or limit aquaculture were also considered, such as distance from ports, marine managed areas (e.g., marine reserves and conservation or protected areas), and navigation routes (Table 1). As a proxy for navigation routes, NOAA 2017 Vessel Transit Counts were used for which each data point represented at least ten instances of recorded vessel passage. All data were collected from online sources (Table 1).

Fixed constraints were applied for each parameter of interest based on the literature and interviews with stakeholders and were chosen based on needs for both aquaculture and wave energy (Table 1). For example, wave power constraint was based on the wave resource needed to power aquaculture operations; wave height constraint was based on wave height limits for the safety of net pens and general operations. For the environmental parameters (i.e., bathymetry, wave height, wave power, and current velocities) and ports, only the constraints (range of value for that parameter) defined in Table 1 were selected. For the other parameters, these areas were excluded as they are likely to conflict with or may require regulatory consideration for co-location. The areas that satisfy all the constraints to co-locate offshore aquaculture and wave energy were identified. All the analyses were performed using ArcGIS 10.7.1.

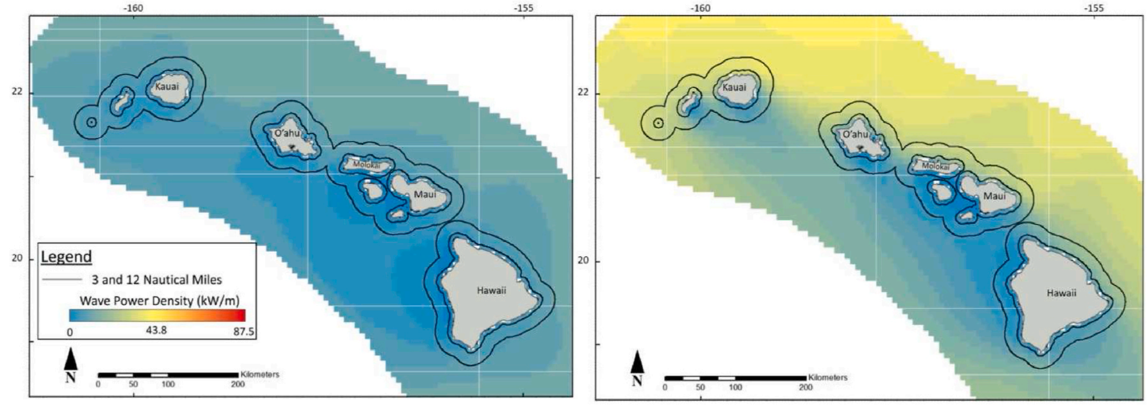
Table 2
Datasets and source of information for the California and Hawaii local assessment, including datasets from the regional assessment and additional datasets available on a local scale, with suitability criteria derived from the literature or interviews. 0 = unsuitable; 1 = suitable.

Area	Parameter	Suitability Score	Criteria	Source
California and Hawaii	Wave height	0	>2.5 m	US Department of Energy Marine Energy Atlas
		1	0–2.5 m	
	Wave power density	0	<20 or >40 kW/m*	US Department of Energy Marine Energy Atlas
		1	20–40 kW/m	
	Current velocities	1	0–1 m/s	Hydrodynamic model HYCOM
		0	>1 m/s	
	Military zones	0	Entire area	US Department of Defense
	Navigation routes	0	Entire area	Marine Cadastre (2020 Vessel Transit Counts)
	Ports	0	>60 km	NOAA Office for Coastal Management
		1	0–60 km	
	Benthic habitat	0	Hard bottom habitat, eelgrass, artificial reefs, kelp	NOAA National Centers for Coastal Ocean Science; California Department of Fish and Wildlife
		1	Soft bottom habitat	
	Species and critical habitat (critical habitat designation, marine sanctuary, Cetacean Biologically Important Areas)	0	Entire area	NOAA Fisheries Office of National Marine Sanctuaries; Marine Cadastre; State of Hawaii Office of Planning and Sustainable Development; NOAA Marine Protected Areas Inventory
	Recreational areas: Dive sites (California) Body surfing sites (Hawaii)	0	Entire area	California Department of Fish and Game State of Hawaii Office of Planning and Sustainable Development
	Underwater cables	0	Entire area	Marine Cadastre
California	Oil and gas platforms	0	Entire area	Marine Cadastre
Hawaii	Fish aggregating devices	0	Entire area	State of Hawaii Office of Planning and Sustainable Development

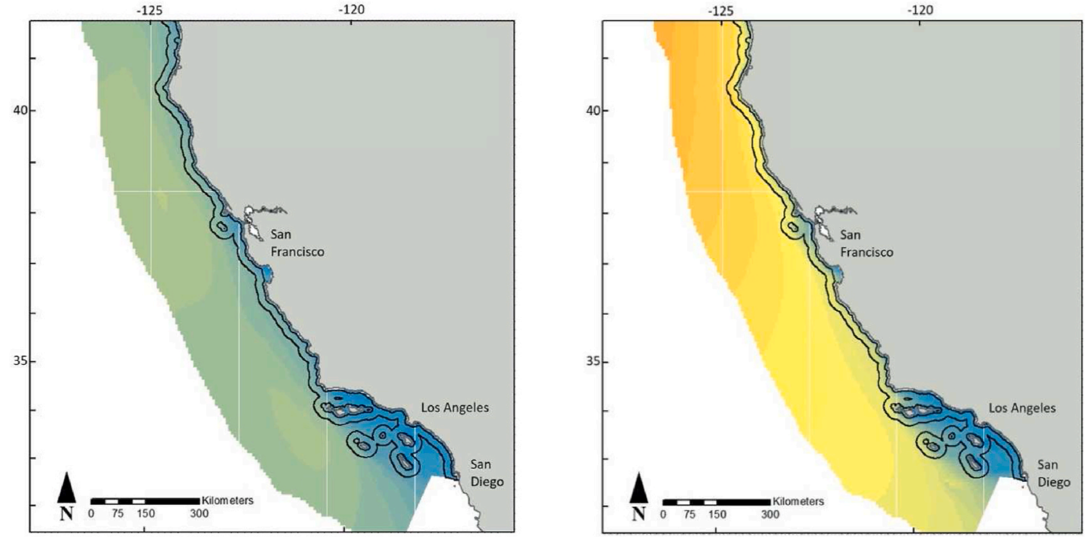
*Wave power density varied based on the desired wave power (e.g., for assessing 5–10 kW/m, 0 was assigned to <5 or >10 kW/m and 1 was assigned to 5–10 kW/m).
NOAA = National Oceanic and Atmospheric Administration.
HYCOM = Hybrid Coordinate Ocean Model.

2.2.2. Local assessment

Feasible local sites for co-location were evaluated based on the favorable areas identified in the regional assessment. In Hawaii, informal interviews were conducted with three local aquaculture experts (industry and government) to inform which of the favorable areas identified should be selected for the local assessment. In addition to the sites in northern California identified as favorable, an analysis was completed in southern California based on the study areas evaluated by the National Oceanic and Atmospheric Administration (NOAA) to identify Aquaculture Opportunity Areas (Morris et al., 2021). At the time of the analysis, several sites were being considered in southern California, and all were included. Because no favorable areas were found in the regional assessment, the Aquaculture Opportunity Areas study



A. Summer – Hawaii B. Winter – Hawaii



C. Summer – California D. Winter – California

Fig. 1. Average wave power density (kW/m) in summer (A) and winter (B) in Hawaii, and in summer (C) and winter (D) in California.

areas under evaluation by NOAA were used to assess if the wave resource might be adequate for wave energy devices if the wave power constraint was reduced below 20 kW/h, down to 5 kW/h.

The local assessment was performed for three areas: Northwest Oahu, Hawaii; northern California, and southern California. All the data layers considered in the regional assessment were included as well as additional local data, all collected from online sources (Table 2). Spatial analyses for all three locations were completed under different wave power scenarios broken down by 5–10 kW/h, 10–20 kW/h, 20–40 kW/h, and 5–40 kW/h. For Hawaii, due to the limited wave energy in summer, the local assessment was confined to the winter months. For California, wave power data were averaged across the year. Preferred sites, noted as suitable for co-location, were identified based on a suitability score. Each parameter was assigned a score of either 0 (unsuitable) or 1 (suitable), which was not weighted due to the uncertainty in the relative importance of each parameter for both wave energy and offshore aquaculture operations (Table 2). For example, for benthic habitat, coral reef and hard bottom habitat are generally not suitable for aquaculture and therefore each data point was assigned a 0; alternatively, each data point for soft bottom habitat (the preferred habitat type) was assigned a 1. The preferred sites for co-location were visualized using heatmaps in QGIS 3.18.3.

Because the regional assessment identified favorable areas, providing a range of scores for suitable parameters in the local assessment allowed for flexibility in identifying preferred sites for co-location within the favorable areas. The analysis presented here did not include an exhaustive list of parameters (e.g., fishing grounds and culturally/historically significant areas or resources were not included) and does not define final areas for co-location. In addition, while some parameters included may present larger barriers to siting, this analysis did not use weights for suitability scores or wholly disqualify any sites as these parameters are often site specific. For example, areas with military zones or marine sanctuaries may ban certain activities, but they were not presumed to preclude aquaculture as an activity. This analysis is a starting point for aquaculture and wave energy developers to choose adequate areas for co-located projects. Depending on the specifications of a wave energy-aquaculture project, the parameters, criteria, and suitability scores may differ from those used in this analysis.

3. Results

3.1. *Characterization of energy use and needs for aquaculture*

The focus of this study was on the ocean-based growth phase of finfish in offshore aquaculture locations. Growth-phase aquaculture operations requiring energy include feeding systems (augers, compressed air, or slurry pumps), circulation pumps, lighting for net pens, winches for moving net pens within the water column, refrigeration, workboats to conduct operation and maintenance around the net pens, transfer vessels, instrumentation for monitoring (which may include autonomous or remote underwater vehicles), and communication equipment. Operations may also include facilities for crew which require energy for heating, lighting, and communication. On-site, growth-phase aquaculture operations generally use a diesel generator to provide onboard electricity, which may run nonstop. These are typically located on the feed barge, a large barge stationed next to the net pens to provide centralized feeding. Hybrid feed barges that add batteries and power management systems are an emerging technology for aquaculture (AKVA 2020).

The available literature on energy used in offshore aquaculture operations was limited and typically reports only the total fuel consumption – incorporating both the fuel for generators (to meet the electricity demand of the offshore operation) and the fuel for transportation. Based on the literature review, the on-site energy demands of a Norwegian coastal salmon operation (Syse 2016; Møller 2019) were assumed to be comparable to the demands of general offshore finfish operations. This did not include transportation energy demands required for aquaculture operations.

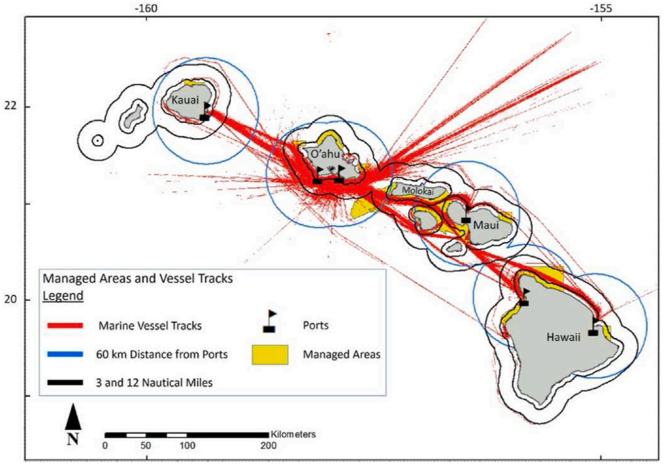
Studies reported the total electric consumption of growth-phase aquaculture operations to be roughly 700 kWh daily for the various electrified loads, with a peak cumulative demand of 100–120 kW during daytime feeding (Syse 2016; Møller 2019). The most energy intensive aspects of the operations were the feed system which accounted for more than 50% of the daily energy within the farm (Syse 2016) as well as the combined lighting, feeding, and other equipment which accounted for 78% of the total energy demand (Møller 2019). A review of specifications for commercially available hybrid feed barges found battery capacities of 115–230 kWh and power management systems with 120 kW inverters (ABB 2019; AKVA 2020). Energy information shared during interviews was consistent with these findings. While no operational data were available to indicate which loads might coincide, information provided during interviews indicated a maximum cumulative demand of roughly 70 kW, which is roughly consistent with the 100–120 kW found in the literature.

With the finding of about 700 kWh/day for current offshore aquaculture energy and power needs, a wave resource of approximately 30 kW/m was estimated as being necessary to meet 100% of the energy needs of an operation. This estimate was based on typical industry assumptions of an MRE system with a 30% capacity factor and combined 3–4 m capture width (Babarit 2015; Lavidas 2020). This needed wave resource was a rough estimate and could be reduced if other energy sources (e.g., wind, solar) were used, if energy efficiency measures were implemented, and/or if a larger capture width or higher capacity factor was used. Based on this information, a wave resource of 20–40 kW/m was used in the spatial analyses to provide a range for a wave resource that could power 100% of on-site aquaculture operations, but does not exceed safe operating conditions. Additional wave resource intervals of 5–10 kW/m and 10–20 kW/m were included in the local assessments to capture locations where a wave energy converter might complement other energy sources to power on-site operations. The wave energy resource of 5–40 kW/m was also compared to the 2.5 m wave height constraint and they were found to not be mutually exclusive; the 2.5 m height constraint coincides with a roughly 40 kW/m power resource for wave periods up to about 12 s (Guillou 2020).

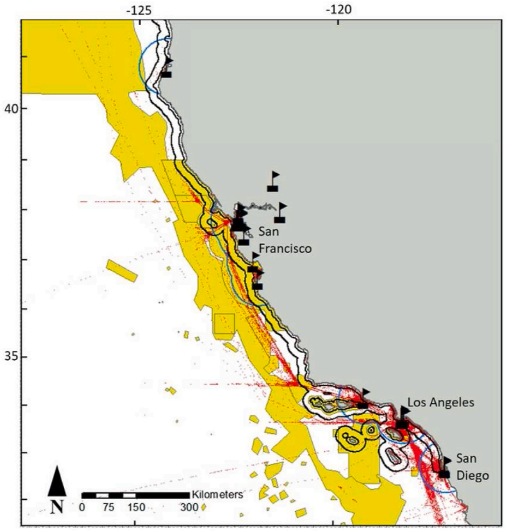
3.2. Regional assessment of favorable areas for co-location

3.2.1. Wave energy resources

Off the coast of Hawaii, average wave power density was lower in summer than winter (Fig. 1). Wave power density ranging from 20 to 40 kW/m was only observed in winter and mainly on the northern shores of the Hawaiian Islands. In both seasons, wave power was higher north of the Hawaiian Islands compared to south (Fig. 1A and B).



A. Hawaii



B. California

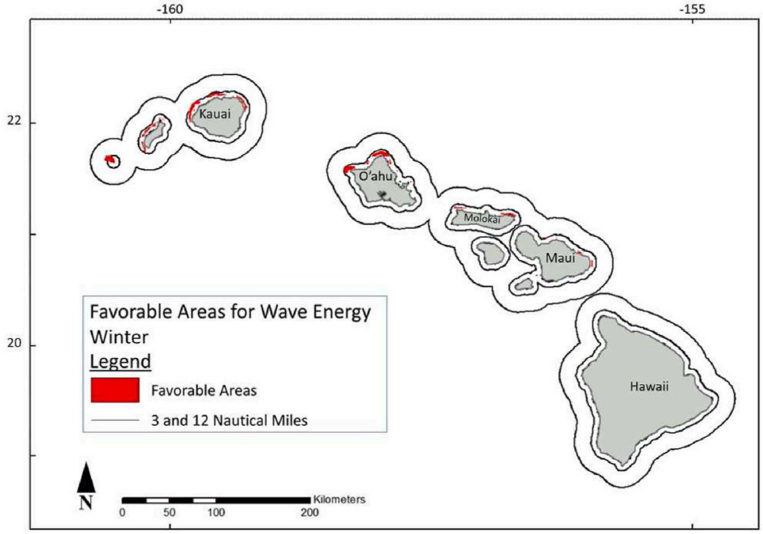
Fig. 2. Regulatory and logistical parameters off Hawaii (A) and California (B). Red lines represent the navigation routes, yellow areas represent managed areas, and black flags are the main ports with blue lines surrounding them representing 60 km distance from the ports.

Off the coast of California, the average wave power density was also lower in summer than in winter (Fig. 1). During both seasons, wave power was low within 3 nm and in the area offshore of Los Angeles (Fig. 1C and D). Wave power density ranging from 20 to 40 kW/m was observed in summer, mainly beyond 12 nm. Maps of other environmental parameters (wave height, bathymetry, and current velocity) are shown in Appendix A.

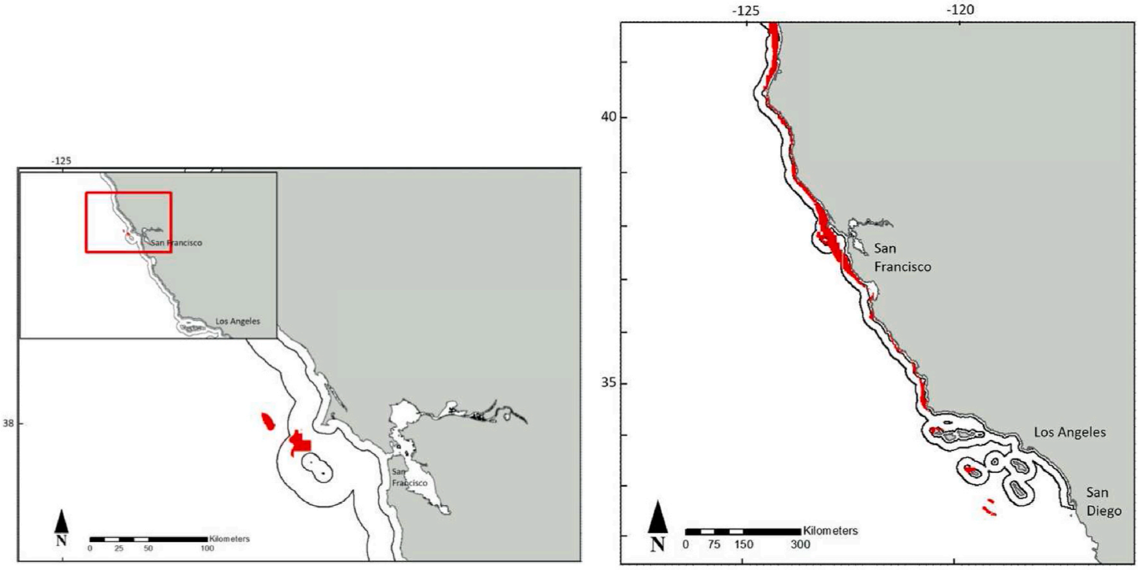
3.2.2. Regulatory and logistical factors

All the regulatory and logistical factors considered for siting were present along the coasts of California and Hawaii (Fig. 2). Off Hawaii, navigation routes were greatest on the south side of O'ahu and between O'ahu, Lanai, and Molokai, with some additional navigation routes among the other islands (Fig. 2A). Most of the Hawaiian Islands fall within 60 km from a port and have managed areas around them.

Off California, navigation routes are present all along the coast but are greatest in southern California with additional navigation routes present off the coast of northern California, mainly off the San Francisco Bay Area. About half of the coastline falls within 60 km of a port, mainly in southern California, the northernmost part of the California coast, and off the coast of San Francisco. Managed areas can be found all along the coast, mostly located beyond 12 nm with some managed areas present within 12 nm of the coast around the islands offshore of Los Angeles and around San Francisco.



A. Hawaii – Winter



B. California – Summer

C. California – Winter

Fig. 3. Favorable areas (in red) for co-locating offshore aquaculture and wave energy off the coast of Hawaii in winter (A) and off the coast of California in summer (B) and winter (C). No favorable areas for co-locating aquaculture and wave energy were found in summer off Hawaii.

3.2.3. *Favorable areas for co-location*

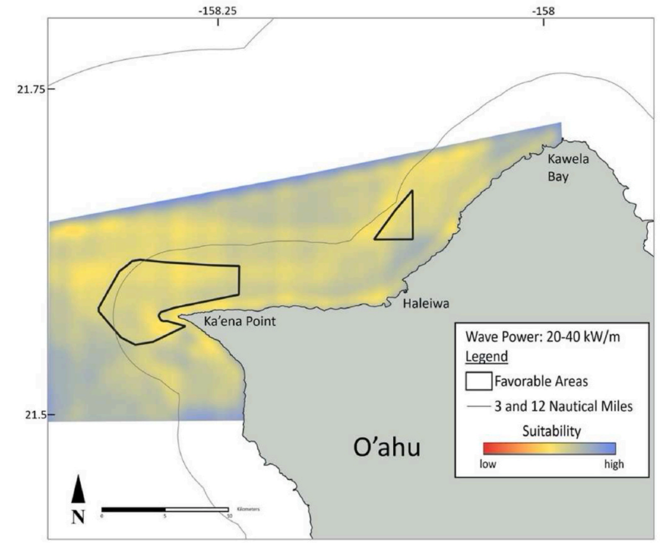
Areas favorable for siting offshore aquaculture and wave energy were identified off the coast of California and Hawaii based on the constraints detailed in Table 1. Overall, there were fewer favorable areas in summer than in winter (Fig. 3). In Hawaii, favorable areas were only found in winter and were mainly located on the northern shore of O'ahu, Kauai, and the two smaller islands to the west (Fig. 3A). Small favorable areas were also observed northeast and northwest of Molokai and northeast of Maui. In California, only two favorable areas were found in the summer, both of which are located off San Francisco (Fig. 3B), unlike in winter when favorable areas were found all along the coast, except off southern California where there were minimal favorable areas (Fig. 3C).

3.3. *Local assessment of suitable sites for co-location*

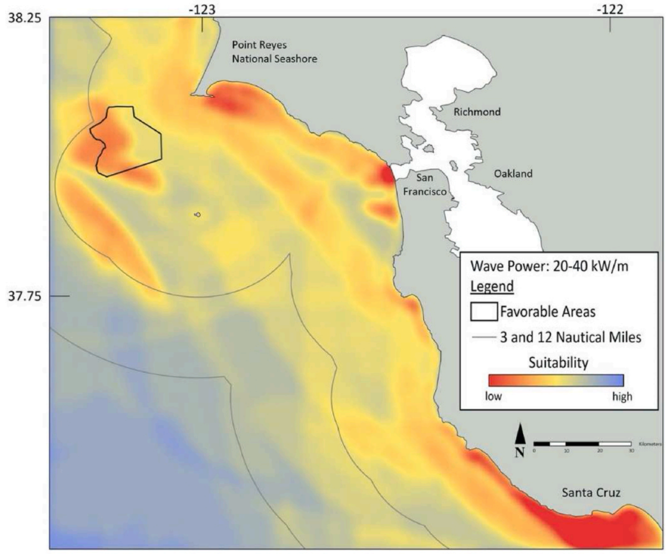
The local assessment analyzed the suitability for co-locating offshore aquaculture and wave energy in areas surrounding the identified favorable areas from the regional assessment: two areas off the northwestern coast of O'ahu in Hawaii and one area off the coast of San Francisco in northern California. Several additional areas were analyzed off the coast of Los Angeles in southern California, based on the Aquaculture Opportunity Area study areas under evaluation by NOAA. Heatmaps show site suitability based on suitability scores described in Table 2 (Figs. 4 and 5).

For both Hawaii and northern California, only the 20–40 kW/m wave power was found to be present throughout the entire area studied in the local assessment (Fig. 4). For southern California, the range of wave power used for the local assessment was broaden to 5–40 kW/m to increase the area that may be feasible for co-location (Fig. 5). Heatmaps of suitability for other wave energy ranges in the three areas are shown in Appendix B.

Off O'ahu, suitability for co-location at wave power between 20 and 40 kW/m was in the medium range for the entire area mapped, with small areas in the high range. Within the favorable areas identified in the regional assessment, there was little variability in suitability scores. Several parameters limited the suitability within the favorable areas: species and critical habitat (whales), benthic habitat (close to the coastline), current velocities, and military zones (north of the areas).



A. Hawaii – Winter



B. Northern California

Fig. 4. Heatmap of the suitability for co-locating offshore aquaculture and wave energy in Hawaii off northwest O'ahu (A) and in northern California off San Francisco (B) with wave power between 20 and 40 kW/m. The shapes outlined in black represent favorable areas for co-location identified from the regional assessment.

In northern California, the suitability for co-location at wave power between 20 and 40 kW/m increased offshore, between 3 and 12 nm. In the favorable area identified from the regional assessment, the eastern half was more suitable for co-location and was in the medium range. Species and critical habitat (green sturgeon, cetacean biologically important areas) limit the suitability in the favorable area. Navigation routes and wave power are additional parameters limiting the suitability in the western part of the favorable area.

In southern California, the suitability for co-location was assessed using the study areas under evaluation by NOAA. Because the wave power constraint was reduced below the estimated 20–40 kW/m needed to power 100% of aquaculture operations down to 5 kW/m, the study acknowledged that these areas would likely require a mix of power supplies (e.g., wave energy paired with solar energy). Even with reducing the power need, suitability along the southern coast of California was in the low range, especially closer to the coast (within 3 nm) but improves further offshore, including around the islands off the coast. Along the coast where the study areas for Aquaculture Opportunity Areas are located, suitability was generally low and the presence of military zones, oil and gas platforms, navigation routes, marine protected areas, and subsea cables limited the suitability for co-location. Off Santa Barbara, wave energy was also a limiting factor with values less than 5 kW/m. Within the study areas for Aquaculture Opportunity Areas, the highest suitability for co-location was found in the two areas located north of Santa Cruz and Santa Rosa Islands.

4. Discussion

This study compiled available information on aquaculture energy demands from the available literature and from aquaculture experts to conclude that wave energy could be a viable source for powering aquaculture operations. The results of this study provide a first assessment of suitable locations in the US, focusing on California and Hawaii, for co-located wave energy and offshore aquaculture projects to advance these novel industries.

4.1. Energy needs

While information about the on-site, non-transportation energy demands of finfish aquaculture operations was limited, there was good agreement across available sources (including interviews with industry leaders and commercial product specifications) about the energy uses and demands of a typical offshore aquaculture operation. Based on this, it was estimated that wave energy is able to provide 100% of the power to such aquaculture operations. However, as more data from offshore operations become available, the assumption used for this study that the energy demands from the coastal salmon operation are comparable to general offshore operations should be revisited.

As the offshore aquaculture industry is expected to grow rapidly, improvements in operational and energy efficiency are anticipated (Chu et al. 2020; Aryai et al., 2021). Reducing energy demand would potentially lower the necessary wave energy resource and expand the geographic range where wave-powered aquaculture could be implemented. A common concern for co-location is the need for sufficient wave resources to provide wave power while also needing a limited wave resource for safe aquaculture operations. This analysis suggests these criteria need not be mutually exclusive, but this dynamic should be explored in future work with a site-specific case study to further understand the maximum acceptable wave environment for these operations, including scenarios where wave energy complements solar or wind generation. Due to the seasonality of wave energy resource in some regions, battery energy storage systems will be needed to distribute stored energy during low wave energy months.

4.2. Spatial assessment for co-location

The spatial analysis revealed that wave power density was the most limiting factor in determining favorable areas off California and Hawaii, followed by bathymetry and the presence of navigation routes or managed areas (mainly in California). Wave height and current velocities were not limiting factors in any of the areas. In the Canary Islands, Weiss et al. (2018) did not incorporate regulatory parameters to identify suitable areas for the development of aquaculture but found that wave height was the main siting constraint. Wave action is often mentioned as a limiting factor for the development of offshore aquaculture development (Pérez et al., 2005; Falconer et al., 2013). There may be a discrepancy between the low energetic wave climate required for aquaculture operations and the necessary wave energy resource to extract power. However, aquaculture developers show increasing interest in using low carbon renewable energy to power their operations. Aquaculture technologies are being developed to be more suitable for offshore operations, such as large-scale, semi-, or fully autonomous, and/or submersible systems (Chu et al. 2020). These systems may use

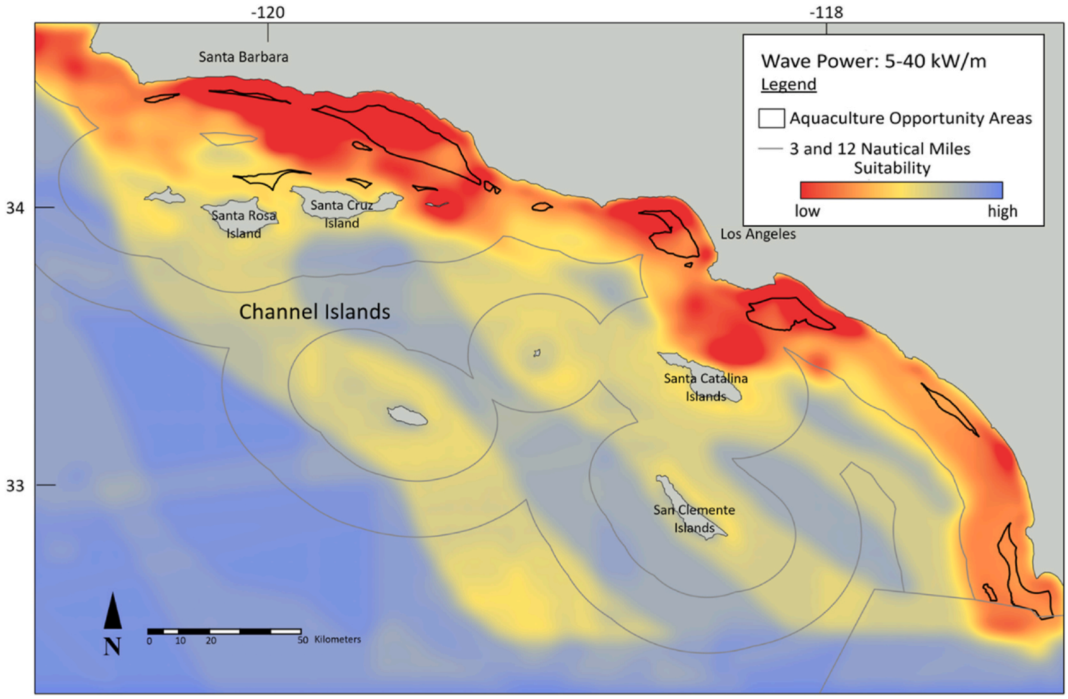


Fig. 5. Heatmap of the suitability for co-locating offshore aquaculture and wave energy off southern California with wave power between 5 and 40 kW/m. The shapes outlined in black lines represent the study areas evaluated by the National Oceanic and Atmospheric Administration to identify an Aquaculture Opportunity Area (Morris et al., 2021).

fully enclosed net pens that submerge for storm events and/or employ autonomous underwater vehicles or remotely operated vehicles for monitoring or operations, which would minimize the risk of failure in larger wave climates. Using renewable energy as a power source for aquaculture could also be an opportunity to label aquaculture products as originating from renewable power sources and potentially increase their market values (Schultz-Zehden et al., 2018). The MRE industry is also considering small scale wave energy devices to generate power from low wave energy resources and for low power stand-alone applications such as offshore aquaculture (Coe et al., 2021; Oikonomou et al., 2021).

In this study, the spatial scale of the areas satisfying all the environmental, regulatory, and logistical constraints for co-location in the regional assessment was largest in California, particularly in the winter. Because no areas were found to be favorable in Hawaii in the summer, potential projects may consider pairing wave energy with other forms of renewable energy, such as solar energy. Hybrid renewable energy solutions for aquaculture and other industries have been studied with increasing frequency but often combine solar and wind energy (Recalde et al., 2019), leaving a need for research on hybrid wave-solar solutions. Building on the favorable areas described in the regional assessment, the local assessment identified both favorable areas off the coast of O'ahu and the eastern portion of the favorable area off the coast of San Francisco in northern California as suitable for co-location. In southern California, there may be opportunities for co-location in the study areas for Aquaculture Opportunity Areas near the Channel Islands, though more suitable areas were found further offshore. While the local assessment showed some sites as more or less suitable, this does not mean that those marked as less suitable should not be explored for siting but rather that there may be additional factors or uses to take into consideration.

There were several limitations to the spatial analyses. Environmental conditions at large scales are simplifications of the ocean system and may omit local factors potentially influencing the intensity of wave and currents, such as local wind conditions. Environmental constraints for wave power and wave height were based on energy needs for large aquaculture salmon farms and may differ depending on the scale of the aquaculture operation and the species of interest. These limitations show the need for data at finer-scale resolution and additional data about energy needs to further home in on potential areas for co-locating offshore aquaculture and wave energy. For the local assessment, results were based on available data which may not include every parameter required to determine if a potential site is suitable for co-location. Other environmental data such as oxygen and water temperature will need to be considered in future analyses targeting specific fish species.

5. Conclusion

This assessment of energy needs and applications for offshore aquaculture provided a better understanding of energy demand and the potential for meeting those demands using wave energy. The estimated demand of 700 kWh/day for current offshore aquaculture operations from the literature can be met by using wave energy depending on the location and season. The information gathered to better understand critical factors for co-locating offshore aquaculture and wave energy indicated a limitation in wave power density particularly in summer.

To our knowledge, the potential to both co-locate and power offshore aquaculture with wave energy has rarely been assessed. In this study, favorable areas for co-location were identified off California and Hawaii as suitable for both offshore aquaculture and wave energy. In the US, other regions such as the East Coast and the Pacific Island territories have sufficient wave energy resources (García-Medina et al., 2021; Seongho et al., 2021) where co-location may be possible. Alaska, which also has a very large wave energy resource, was considered for inclusion in this study, but finfish aquaculture is not allowed in state waters and the regulatory environment would make it challenging to site finfish aquaculture beyond 3 nm.

As aquaculture expands to large, offshore operations, understanding local and regional regulatory environments in potential areas for co-location, including social acceptance, will be key to responsibly advancing the sector. Marine spatial planning will be necessary to reduce potential conflicts as marine uses increase. Similarly, involving key stakeholders before project deployments will help successfully expand aquaculture with support from marine users (Kim et al., 2012; Lester et al., 2018b). Future studies will benefit from including social and economic considerations and understanding areas where the political and social climates are favorable for co-location.

This study was a first step in understanding the energy needs for offshore aquaculture, and how various factors can help determine suitable areas for co-location. Given the study results showing potential for co-location in the US and the industry interest, it would be prudent to pursue follow-up investigations of favorable areas for co-locating mutually supportive offshore aquaculture and wave energy endeavors. An assessment of challenges for co-location is needed to drive further research opportunities such as a cost feasibility assessment for deploying MRE technologies to power offshore aquaculture. With aquaculture projected to grow worldwide, increasing the understanding and feasibility of powering offshore aquaculture with wave energy can help contribute to combatting climate change by switching to renewable energy sources.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A and B. Supplementary data

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