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Abstract

In the United States (US) Caribbean Sea, Puerto Rico and the US Virgin Islands (USVI) are planning to transition to renewable energy. Being surrounded by water, the use of marine energy within Puerto Rico and the USVI represents an opportunity to increase renewable energy usage. Marine energy includes wave, tidal, and current energy as well as thermal and salinity gradient energy, and has a large potential to provide reliable and efficient power. While marine energy is usually perceived to bring power to the grid, it can also be used to power activities at sea, particularly offshore aquaculture. In the US Caribbean islands, the development of co-located offshore aquaculture and marine energy could help boost the ocean economy. This study highlights a real-world assessment of the suitability to co-locate offshore integrated multi-trophic aquaculture (IMTA) and wave energy off Puerto Rico and the USVI. The feasibility for co-location was determined through a spatial analysis to identify suitable areas for co-location, field work to collect environmental data, and a readiness analysis of wave energy devices. Combining key environmental, regulatory, and logistical parameters, the spatial analysis identified potential suitable areas for co-location off the coast in the northwest corner of Puerto Rico, northwest of Culebra, east of Vieques, and north of St. Thomas in the USVI. Wave energy was identified as the most limiting parameter for co-location in the study area. The wave energy data collected were comparable to the model predictions, showing the usefulness of fine-scale environmental conditions from wave models to assess the feasibility for co-location. Through the combination of spatial analysis, environmental monitoring, and information on wave energy device readiness, several key components for the technical feasibility of co-locating offshore IMTA and wave energy have been demonstrated in the US Caribbean islands.

1. Introduction

The economies of the United States (US) Caribbean islands, Puerto Rico and the US Virgin Islands (USVI), rely partly on ocean-related activities such as fisheries, tourism, and marine transportation (Clements *et al* 2016). Small-scale fisheries have been impacted by Hurricane María in 2017 and the COVID-19 crisis (NOAA Fisheries 2020, Stoffle *et al* 2020, Gómez-Andújar *et al* 2022). Hurricane María also caused a decrease in commercial landings, loss in revenue, and extended power outages (Agar *et al* 2020). Electricity infrastructure in the US Caribbean relies heavily on fossil fuels. With the increase in intensity and frequency of hurricanes, Puerto Rico and the USVI are looking to transition to renewable energy sources (Puerto Rico Energy Public Act 2019, National Renewable Energy Laboratory 2020, Baggu *et al* 2024).

In mid-2023, renewable energy provided between 3% to 5% of Puerto Rico's electricity (Baggu *et al* 2024). The country has set renewable energy targets of 60% by 2040 and 100% by 2050 (Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy in Puerto Rico 2021). Currently, Puerto Rico uses solar, land-based wind, and hydropower as renewable energy sources (Massol-Deyá *et al* 2018, U.S. Energy Information Administration 2024a). In the USVI, less than 10% of generated electricity is supplied by renewable resources, all of which come from solar energy (U.S. Energy Information Administration 2024b). The renewable energy target for the USVI is 50% by 2044 (Black and Veatch 2020). Being surrounded by ocean, the use of marine energy within these islands represents an opportunity to increase renewable energy usage.

Marine energy includes wave, tidal, and current energy as well as thermal and salinity gradient energy. Low-latitude geographies like Puerto Rico and the USVI are typically most suited for generating energy from the power of waves or thermal gradients in the ocean (Osorio *et al* 2016, Rusu and Rusu 2021, Ticona Rollano *et al* 2025). Marine energy can be used to power the electrical grid, remote locations and islands, or offshore industries (LiVecchi *et al* 2019). There are several challenges to deploying marine energy, including low technology readiness, permitting challenges, particularly around environmental concerns, and potential conflicts with existing uses (de Groot *et al* 2017, Garavelli *et al* 2024). While both wave energy and ocean thermal energy conversion present possibilities, wave energy technologies are further developed and have been successfully deployed in several locations around the world (IEA-OES 2024). Around Puerto Rico and the USVI, the wave energy resource has been assessed (Canals Silander and García Moreno 2019, Kilcher *et al* 2023), but the feasibility of wave energy to power offshore industries is not well studied.

One of the offshore industries that can be powered by wave energy is offshore aquaculture (Freeman *et al* 2022, Garavelli *et al* 2022). Aquaculture is projected to grow worldwide (FAO 2024) and the increased conflicts and pollution issues nearshore have contributed to developing aquaculture operations offshore (Fujita *et al* 2023, Zheng *et al* 2024). As the aquaculture industry moves offshore, operations are expected to scale up, leading to increased energy demands and associated costs (Menicou and Vassiliou 2010). Since most aquaculture operations currently rely on fossil fuels (Freeman *et al* 2022), using locally available renewable energy on-site could offer significant benefits by reducing operational costs and environmental impact. Offshore aquaculture growth in the US has been slow with only two commercial offshore farms and a few experimental and proposed farms (Fujita *et al* 2023). Siting issues, permitting challenges, and governance are often mentioned as the main barriers aquaculture developers face (Lester *et al* 2018, Rubino 2023). In the US Caribbean islands, interest is growing in establishing a sustainable aquaculture industry to locally produce seafood for local and export markets. However, there is a need for responsible planning and siting to prevent environmental impacts in the aquaculture industry (Price and Beck-Stimpert 2014). The development of co-located offshore aquaculture and marine energy in Puerto Rico and the USVI could enhance the ocean economy and provide additional revenue streams for local fishers.

The first US feasibility assessment on co-locating offshore aquaculture and wave energy was conducted off the coast of California and Hawaii (Garavelli *et al* 2022) and focused on spatial analysis to identify potentially suitable areas. Similar methods were applied off the coast of Maine to identify sites for a wave-powered aquaculture farm, and found that spatial conflicts and wave energy availability influenced project siting and costs (Ewig *et al* 2025). Other co-location assessments for offshore aquaculture with offshore wind considered the co-use of space but not the feasibility of using offshore wind energy to power aquaculture operations (Gimpel *et al* 2015, Weiss *et al* 2018, Stockbridge *et al* 2025). Conversely, cost and power needs were evaluated for wave energy and offshore aquaculture co-location off the coast of Portugal, but a spatial analysis was not considered (Clemente *et al* 2023).

Our study focuses on co-locating offshore integrated multi-trophic aquaculture (IMTA) and wave energy. Co-location is the sharing of space and/or resources, and this study specifically includes wave energy providing power to the IMTA operation. IMTA allows for holistic co-farming of fed species (e.g. fish), extractive species (e.g. shellfish), and macroalgae, increasing the efficiency and product diversification of aquaculture (Buck *et al* 2018). IMTA allows for the reutilization of byproducts between species with, for example, the use of biofilter organisms (shellfish) to eliminate fish waste materials (Ghosh *et al* 2025). Through an ecosystem-oriented approach, IMTA systems decrease the environmental impacts of aquaculture and enhance its sustainability and likely its social acceptance (Sanz-Lazaro and Sanchez-Jerez 2020). Because the sizes and types of IMTA systems vary and it is important to consider coastal communities' preferences and needs when selecting such features, our study does not focus on a specific system or scale for this research.

To assess the feasibility of co-locating offshore IMTA and wave energy off the coast of Puerto Rico and the USVI, this study employed spatial analysis, environmental monitoring, and technological specifications of wave energy devices. Potential suitable areas for co-location were identified at the regional scale using modeled and observed data of key parameters. Then, environmental monitoring was conducted at a representative site off the coast of Puerto Rico, and observed wave climate data were compared to model predictions. Finally, results from a request for information about wave energy devices were analyzed to evaluate the readiness of existing devices to power offshore IMTA.

2. Methods

2.1. Suitability for co-location

2.1.1. Hydrodynamic data

Hydrodynamic data were compiled to include significant wave height, wave power density, and current velocities. Wave power density and significant wave height were obtained from the CARICOOS nearshore wave model (CNWM), based on the simulating waves nearshore spectral wave model (Booij *et al* 1999, Canals Silander and García Moreno 2019). The model has an unstructured mesh with variable resolution ranging from 500 m offshore to 20 m near the coast.

Located in the northeastern Caribbean Sea, Puerto Rico experiences significant seasonal variability in the wave climate (Canals Silander and García Moreno 2019). To account for this variability, data from a similar wave hindcast were used but these were based on Wavewatch III (Tolman 2014) and executed at Pacific Northwest National Laboratory (PNNL) for 41 years (1979–2020) (Kilcher *et al* 2023). This model (henceforth PNNL-NREL model) was configured with a 4 arc-second resolution of roughly 7.05 km by 7.41 km at 18°N in the zonal and meridional directions, respectively, a lower resolution than the CNWM. To take advantage of the high resolution of the CNWM model, data from the PNNL-NREL model were interpolated into the CNWM mesh. Data were bias-corrected based on the ratio of mean wave power density and significant wave height. When comparing the average wave conditions, the bias correction was applied to the monthly averaged wave fields to partially account for missing shelf scale and nearshore physics in the PNNL-NREL hindcast. In summary, the spatial variability of the wave energy resource was obtained from the long-term average results from CNWM and the seasonality was obtained from the PNNL-NREL hindcast.

Monthly averaged ocean currents were obtained from the American SEAS (AMSEAS) model based on the Navy Coastal Ocean Model and operated by the Fleet Numerical Meteorology and Oceanography Center for the US Navy. The model has a horizontal spatial resolution of 1/30° which at 18°N is equivalent to 3.5 km by 3.7 km in the zonal and meridional directions, respectively. The model has 40 layers in the vertical direction from the surface to 5000 m depth. The model resolution is variable with increased resolution near the surface[3]. Data from 2021 were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information. Ocean current velocities were calculated as the vector sum of the zonal and meridional components of the velocity and then time averaged over each calendar month.

2.1.2. Parameters included in the spatial analysis

Environmental, regulatory, and logistical parameters relevant for co-locating offshore IMTA and wave energy were included in the spatial analysis and are described in table 1. Relevant parameters were identified from the literature and stakeholder input (see Garavelli *et al* 2022). The data for these parameters were gathered through publicly available sources (see table 1). In addition, stakeholders in Puerto Rico were consulted twice at an online webinar in August 2022 and at an in-person workshop in San Juan, Puerto Rico, in February 2023 to identify additional parameters and associated data to include in the spatial analysis. The stakeholders included members of federal agencies, universities, non-governmental organizations, and local non-profit organizations.

Key environmental parameters included were wave height which is relevant for the viability of aquaculture net pens, wave power density for wave energy to be feasible, current velocities for fish feeding and safe operations (e.g. diving for operation and maintenance needs around the IMTA structure), bathymetry for the ideal depth of a co-located project, and benthic habitat for reducing environmental effects by prioritizing soft bottom. Other environmental parameters that are important for aquaculture, such as oxygen or temperature, were not included as our analysis focused on general considerations for aquaculture and wave energy operations and was not specific to any species and their environmental/rearing requirements. Regulatory and logistical parameters that might restrict or limit aquaculture or wave energy or may be challenging from a permitting perspective were also considered and are described in table 1, such as navigation routes, distance from ports, critical habitat, marine protected areas, submarine cables, and danger zones and restricted areas. As a proxy for navigation routes, NOAA 2019 vessel transit counts were used for each data point representing at least ten recorded vessel passage instances. Vessel counts were also examined based on vessel type (e.g. cargo, fishing, passenger, pleasure craft and sailing, tanker, tug and tow). Danger zones and restricted areas define 'a water area

[3] AMSEAS vertical grid: 0, 2, 4, 6, 8, 10, 12, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 125, 150, 200, 250, 300, 350, 400, 500, 600, 700, 800, 900, 1000, 1250, 1500, 2000, 2500, 3000, 4000, and 5000 m.

Table 1. Parameters of interest and associated constraints used to identify suitable areas for co-locating offshore integrated multi-trophic aquaculture (IMTA) and wave energy off the coast of Puerto Rico and the US Virgin Islands.

Parameter	Constraint	Source data	Suitability score	Score rationale
Wave height (average)	0–2.5 m	Wave hindcast model	1	Expert input (Garavelli *et al* 2022)
	>2.5 m		0.1	
Wave power density (average)	<5 kW m^{-1}	Wave hindcast model	0	Expert input (Garavelli *et al* 2022)
	5–30 kW m^{-1}		1	
Current velocities (average)	0–1 m s^{-1}	AMSEAS model	1	Expert input (Garavelli *et al* 2022)
	>1 m s^{-1}		0.1	
Bathymetry	<15 m	NOAA National Geophysical Data Center US. Coastal Relief Model Vol. 9	0	Expert input (specific for IMTA)
	15–80 m		1	
	>80 m		0.1	
Benthic habitat	Hard bottom, submerged vegetation, coral reef	NOAA National Centers for Coastal Ocean Science	0	NOAA Aquaculture Opportunity Area (AOA) (Riley *et al* 2021)
	Soft bottom (sand & mud)		1	
Navigation routes (more than 10 vessel counts per year)	Presence (cargo, fishing, passenger, pleasure craft and sailing, tanker, tug, and tow)	NOAA Fisheries	0.1	NOAA AOA (Riley *et al* 2021)
	Presence (recreational, unknown)		0.5	
Distance to ports	0–40 km	US. Geological Survey	1	NOAA AOA (Riley *et al* 2021) Expert input (specific for IMTA)
	40–60 km		0.5	
	>60 km		0.1	

(Continued.)

Table 1. (Continued.)

Artificial reefs (152 m setback)	Presence	Marine Cadastre	0	NOAA AOA (Riley *et al* 2021)
Fishing aggregating devices	Presence	Puerto Rico Fishing Aggregating Devices System	0	NOAA AOA (Riley *et al* 2021)
Ocean disposal sites	Presence	Marine Cadastre	0	NOAA AOA (Riley *et al* 2021)
Pilot boarding areas + stations (500 m setback)	Presence	Marine Cadastre	0	NOAA AOA (Morris *et al* 2021)
Aids to navigation (500 m setback)	Presence	Marine Cadastre	0	NOAA AOA (Riley *et al* 2021)
Unexploded ordnance and formerly used defense sites (500 m setback)	Presence	Marine Cadastre	0	NOAA AOA (Riley *et al* 2021)
Anchorage areas	Presence	Marine Cadastre	0	NOAA AOA (Riley *et al* 2021)
Submarine cable (500 m setback)	Presence	NOAA Fisheries	0	Best & Kilcher (2019), NOAA AOA (Riley *et al* 2021)
Wrecks and obstructions (152 m setback)	Presence	Marine Cadastre	0	NOAA AOA (Riley *et al* 2021)
Species critical habitat	Presence	NOAA Fisheries	0.1	NOAA AOA (Riley *et al* 2021)
		Green sea turtle		
		Leatherback Turtle		
		Loggerhead Sea Turtle		
		Hawksbill Turtle		
		Elkhorn and Staghorn Coral		
		Nassau Grouper		
Protected areas	Presence	US. Department of Agriculture Forest Service	0.1	NOAA AOA (Riley *et al* 2021)
Military zones	Presence	North Carolina State University Libraries	0.5	NOAA AOA (Riley *et al* 2021)
Danger and restricted zones	Presence	Marine Cadastre	0.5	NOAA AOA (Riley *et al* 2021)

(or areas) used for target practice, bombing, rocket firing or other especially hazardous operations, normally for the armed forces' (US. Government, 1993). In addition, state (3 nm for USVI and 9 nm for Puerto Rico) and federal water (12 nm) boundaries were included in all maps because they represent a key regulatory factor in evaluating the feasibility for co-location.

2.1.3. Potential suitable areas for co-location

Potential suitable areas to co-locate offshore IMTA and wave energy were identified based on the number of parameters within the study area, and the constraints and suitability scores for each. Stakeholders were consulted twice to help identify suitable areas. The first consultation took place at the in-person workshop in 2023, where stakeholders were asked to recommend additional datasets and participatory mapping was carried out to note possible areas around Puerto Rico for co-location. A second consultation was held in November 2023 to receive feedback on the preliminary spatial analysis after incorporating new datasets identified during the in-person workshop.

Fixed constraints and suitability scores were applied for each parameter based on the literature and expert input (see Garavelli *et al* 2022) (table 1). For example, the wave power density constraint was based on the estimated wave resource needed to power aquaculture operations. Garavelli *et al* (2022) estimated that a wave energy resource of 30 kW m^{-1} would be required to fully meet the daily energy demand of 700 kWh for an offshore aquaculture operation. Davonski (2024) estimated peak energy demands ranging from 45–709 kWh d^{-1} for IMTA system sizes with 2–12 net pens, which could be met by one or more wave energy devices. Based on these estimates, the maximum available wave power density around Puerto Rico (30 kW m^{-1}) is therefore sufficient to meet the energy needs of offshore IMTA. Wave height constraint (0–2.5 m) was identified by aquaculture experts based on wave height limits for net pens and operations safety; similarly, current velocities constraint (0–1 m s^{-1}) was based on limits for aquaculture scuba divers' safety.

Some constraints were added based on being within a certain distance of a parameter or at a minimum distance away from or entirely outside a parameter. For example, the distance from ports (0–40 km) was identified by experts as the ideal range that would allow a round-trip between a port and an offshore co-location site to be completed within a single day. Additionally, some constraints were based on the need to avoid a specific parameter or area, such as for benthic habitat where hard bottom, submerged vegetation, and coral reef habitat should be avoided. Suitability scores were assigned to each parameter based on these identified constraints and were selected based on a similar methodology previously applied to identify Aquaculture Opportunity Areas off the coast of southern California and in the Gulf of Mexico (Morris *et al* 2021, Riley *et al* 2021). Scores range from 0 to 1, with 0 representing low suitability and 1 representing high suitability (table 1).

All data layers were clipped to the study area, centered on Puerto Rico and the USVI, and running approximately 230 km north to south and 440 km east to west. A multi-criteria overlay analysis was carried out to identify suitable areas for co-location of IMTA and wave energy. First, all layers were converted to raster format so that the constraint for each parameter could be set to the identified suitability score designated in table 1. All layers were then overlaid to add the suitability scores of each layer together and display areas of high and low convergence of suitability. Maps of suitability for co-location were clipped to the wave power density layer based on the constraint of 5–30 kW m^{-1} as an adequate wave energy resource is required for co-location to be feasible. Potential suitable areas for co-location with a maximum suitability score and a size of at least 1 km^2 were considered.

2.2. Environmental monitoring

Much of the spatial analysis relies on large-scale numerical models to provide data at local scales. To investigate the local conditions that might not be well represented in a large-scale model, environmental monitoring was carried out using an instrumentation package designed to provide site-specific data that could inform a future co-located marine energy and aquaculture project. The goals of the environmental monitoring were to test a simple instrumentation package's efficacy for characterizing locations suitable for aquaculture and wave energy, as well as to develop an understanding of model-observation agreement in the region. A representative location off the west coast of Culebra (18°23′16.3″N, 65°23′24.0″W) was selected as the field work site using the spatial analysis suitability results (see section 3.3). The choice of potential locations was limited to locations with water depths of less than 50 m to simplify the field work. The site was monitored for around three months.

The instrumentation package was installed off the coast of Culebra on 27 July 2023 and included a Sofar Spotter buoy to measure waves (see supplementary information). The Sofar mooring was designed with a 68 kg anchor and a mid-water float to reduce the impact of the mooring on the wave measurements. The Sofar Spotter buoy was programmed to transmit wave data hourly via satellite. The Sofar Spotter buoy was deployed for three months on the mooring and was recovered on 4 November 2023. The significant wave height and mean wave energy period recorded by the buoy were compared with the CNWM at the same coordinates as the buoy (Canals Silander and García Moreno 2019). The mean wave power density was calculated for the entire duration of deployment and compared to the modeled wave data from the PNNL-NREL model averaged from 27 July to 4 November for all the available hindcast months (Kilcher *et al* 2023) (see section 2.1). Because the PNNL-NREL model did not include 2023, the comparison can only inform how 2023 differed from the long-term hindcast used in the study but does not serve to characterize the model results further.

2.3. Wave energy device suitability

To further understand the suitability for co-locating offshore IMTA and wave energy, a request for information was issued to determine whether existing wave energy companies would be interested in pursuing wave energy devices for offshore aquaculture purposes. Within the request for information, the field work site in Puerto Rico was highlighted as a potential location for aquaculture, alongside a site in California (see Garavelli *et al* 2022) to allow for a broad understanding of wave climates feasible for different devices. Information was requested related to the rated power, the size of the device, the wave requirements, the technology readiness level, and the lead time to manufacture the device. While the responses that could identify individual devices were confidential, the anonymized information was used to understand the market for wave energy devices that are suitable for co-location. Inputs received from wave energy companies were summarized in different categories: technology description, testing, siting, and delivery timeline. These inputs were used to evaluate whether or not there were suitable existing devices for the co-location of wave energy and offshore aquaculture.

3. Results

3.1. Relevant parameters for co-location

A subset of key environmental, regulatory, and logistical parameters is described below for co-locating offshore IMTA and wave energy off the coast of Puerto Rico and the USVI. The other parameters are described in Supplementary Material.

Higher values of wave power density are observed north of Puerto Rico and the USVI and lower values dominate the southern side of the islands and nearshore areas (figure 1). This is observed throughout the year with values being higher in winter than in summer (see supplementary information). Wave power densities below 5 kW m^{-1} were excluded from the map as a wave resource above 5 kW m^{-1} is necessary to produce wave energy for powering offshore aquaculture operations (table 1). Wave power densities above 30 kW m^{-1} are not found off the coast of Puerto Rico or the USVI.

Figure 2 shows artificial reefs, fish aggregating devices, submarine cables, critical habitats for endangered species, habitat areas of particular concern, and marine protected areas. Artificial reefs are mostly on the southwestern corner of mainland Puerto Rico with a few near San Juan. Fish aggregating devices are on the northern side of mainland Puerto Rico. Submarine cables exist mainly to the north of Puerto Rico as well as between Puerto Rico and the USVI and all around the USVI. Habitat areas of particular concern and marine protected areas often overlap and are spread throughout the study area with the most notable one around Isla de Mona in Puerto Rico. Critical habitats are typically close to shore surrounding all the islands in the study area and exist between the mainland and the islands of Culebra and Vieques.

3.2. Potential suitable areas for co-location

Suitability scores are shown around Puerto Rico and the USVI for wave energy resources higher than 5 kW m^{-1} (figure 3). Most areas with sufficient wave energy resources around Puerto Rico and the USVI fall within the moderate to high range of suitability with the highest values (suitability score = 19.5) clustered to the east of Puerto Rico around Culebra and to the east of Vieques, the northwest corner of Puerto Rico, and the north of St. Thomas in the USVI.

3.3. Environmental monitoring

The environmental monitoring campaign was performed in one of the identified potentially suitable areas for co-location to serve as a representative site. Due to its high suitability score (19.5; figure 3), the area off the northwest coast of Culebra was selected (figure 4).

The CNWM wave model and Sofar Spotter buoy generally reported similar significant wave heights and mean periods with only a few minor deviations evident throughout the environmental monitoring period (figures 5(a) and (b)). Wave power density is also largely the same (figure 5(c)), though the model underpredicted two periods of elevated power density in early September and the end of October which correspond to underpredicted significant wave heights (figure 5(a)). A linear regression comparing the wave heights for the model and from the observed buoy data indicates that, generally, agreement is best at lower ($<$8 s) wave energy periods, though the overall goodness-of-fit of 0.69 indicates good model performance (figure 6).

Compared with predictions from the 41 year hindcast and 2023 CNWM models, the observed mean wave power density in August, September, and October 2023 was higher (table 2). Particularly, observations were twice as high in September than in the hindcast model. This could be attributed to model bias but is likely a result of interannual variability

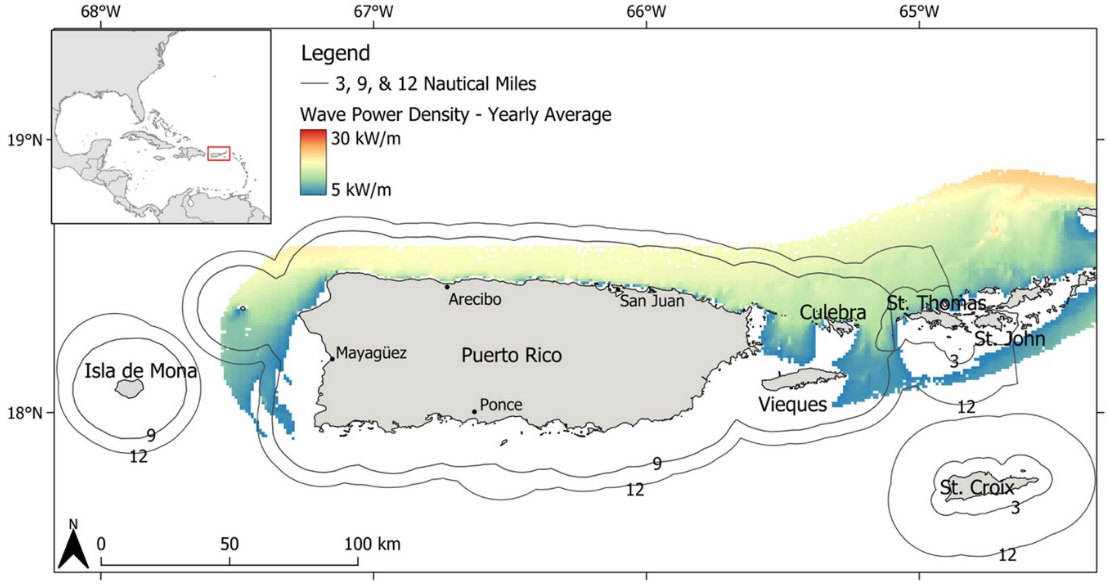

Figure 1. Annual wave power density around Puerto Rico and the US Virgin Islands between 5 kW m^{-1} (blue) and 30 kW m^{-1} (red). Dark grey lines represent the 3 nm (US Virgin Islands) and 9 nm (Puerto Rico) state and 12 nm federal water boundaries.

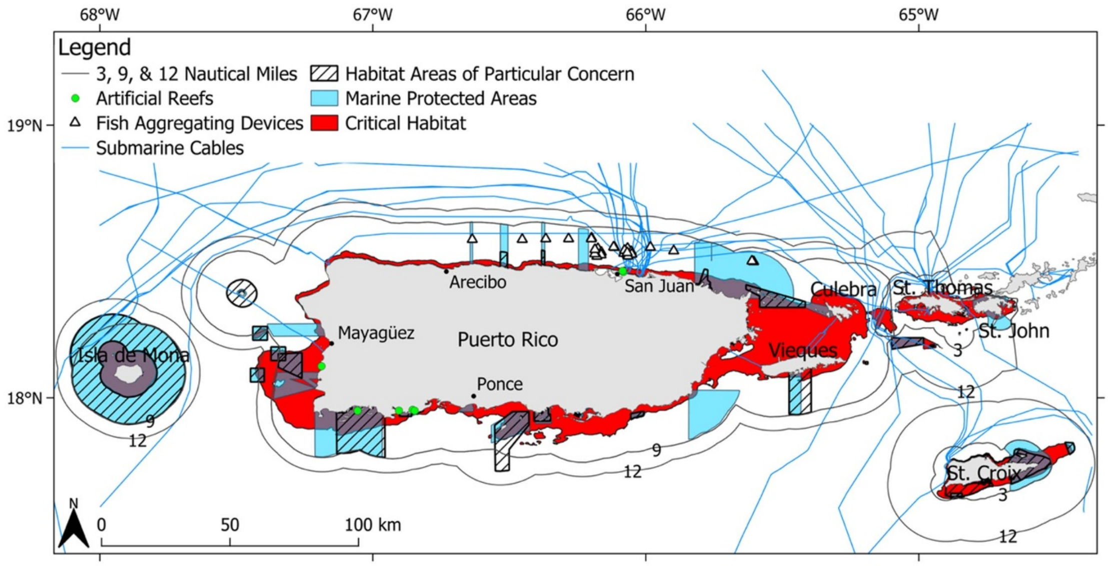

Figure 2. Artificial reefs (green circles), fish aggregating devices (triangles), submarine cables (blue lines), habitat areas of particular concern (hatched areas), marine protected areas (blue areas), and critical habitat (red areas) around Puerto Rico and the US Virgin Islands.

captured in the hindcast averaging. The noticed trend of reduced wave power density in summer (August) and increased in autumn (September, October) holds for the observations and both models.

3.4. Wave energy devices for co-location

16 responses from wave energy companies, with varying levels of detail, were analyzed to understand each device's potential for co-location. Most of the devices were point absorbers (13 responses), followed by surge and pitch (1), oscillating water column (1), pressure differential (1), and one that was not specified. Nine companies indicated a lead time of 18 months or less for their device to be delivered, indicating that an aquaculture-scale device could be tested for demonstration purposes in the near future. Initial analysis of the responses shows that larger devices are capable of converting more power, likely because of their large capture width. Most responses were for devices that would produce between 1 kW and 250 kW (figure 7). A 250 kW device would need to be calibrated for each site to understand total power production.

Three companies indicated that they had designed or modified their device with aquaculture in mind or could do so based on the description of the use case

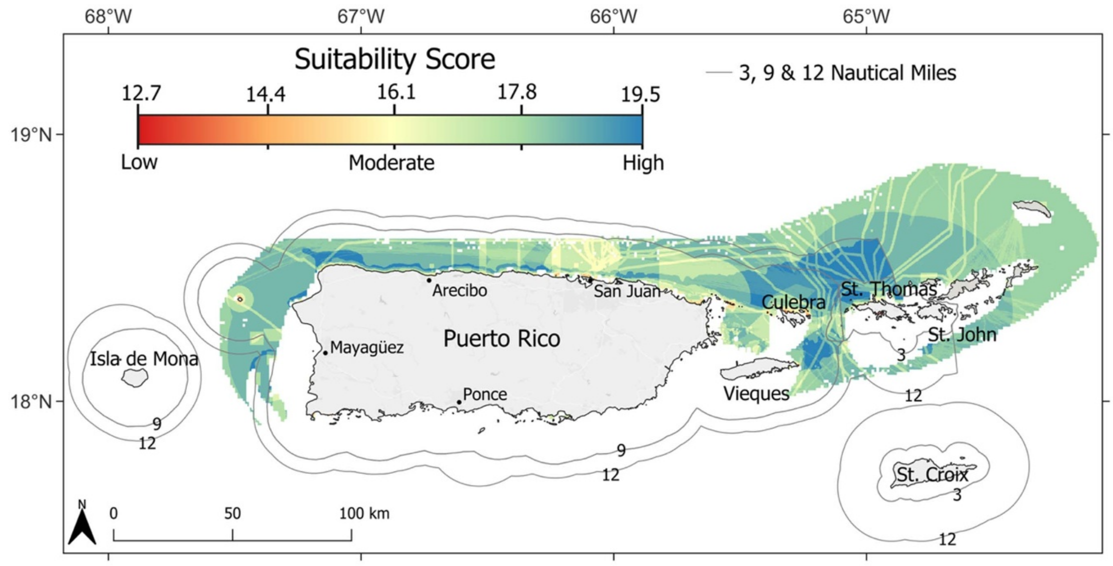

Figure 3. Heatmap of suitable areas to co-locate wave energy and offshore integrated multi-trophic aquaculture. The map is clipped to display only areas with suitable wave power density (5–30 kW m^{-1}).

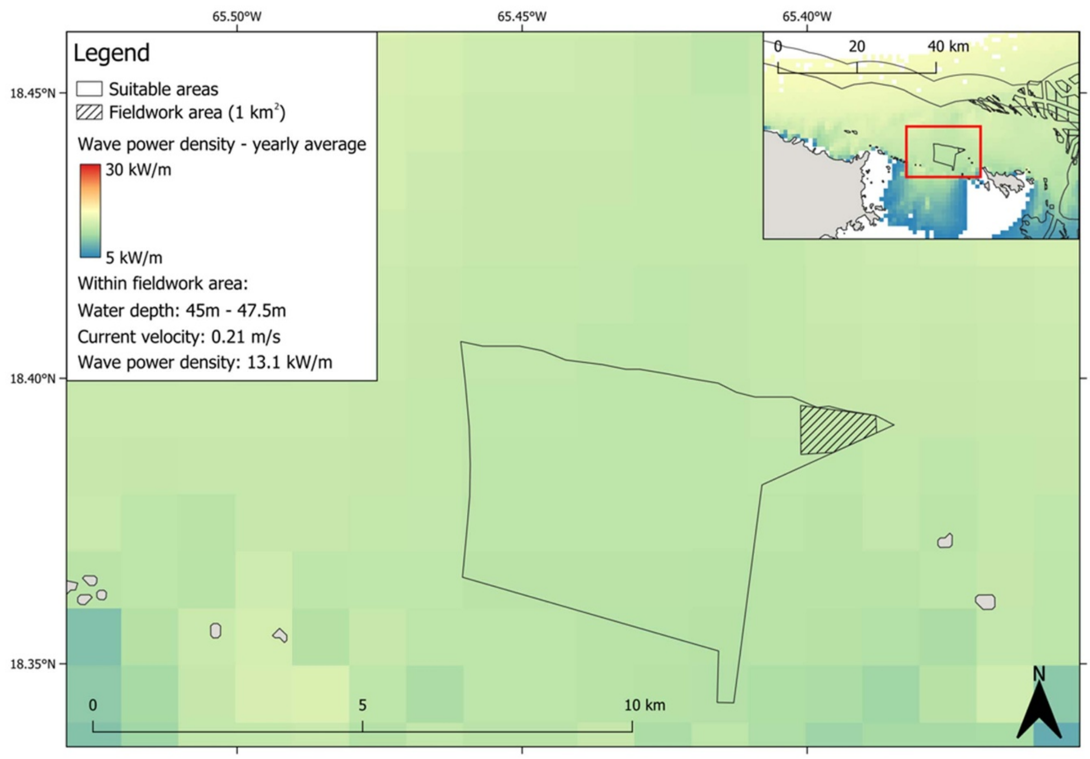

Figure 4. Map showing the location of environmental monitoring (field work) in Puerto Rico off the northwest coast of Culebra within the suitable area (black line) previously identified in this region (see figure 3). The striped pattern indicates the field work location (data collection was performed from 27 July 2023 to 4 November 2023). Yearly average wave power density in the region is indicated and specific data (water depth, yearly average current velocity, yearly average wave power density) within the field work area are highlighted.

in the request for information. Wave energy mooring designs varied, with some planned to be integrated into an aquaculture system and others planned to be moored separately. While model predictions of the wave characteristics and other metocean data were provided, the companies described additional data that they might need to site their devices. These data included bathymetry, current velocity, site logistics (such as distance to ports or other facilities), environmental data (such as the presence of endangered species or critical habitat), and seabed data.

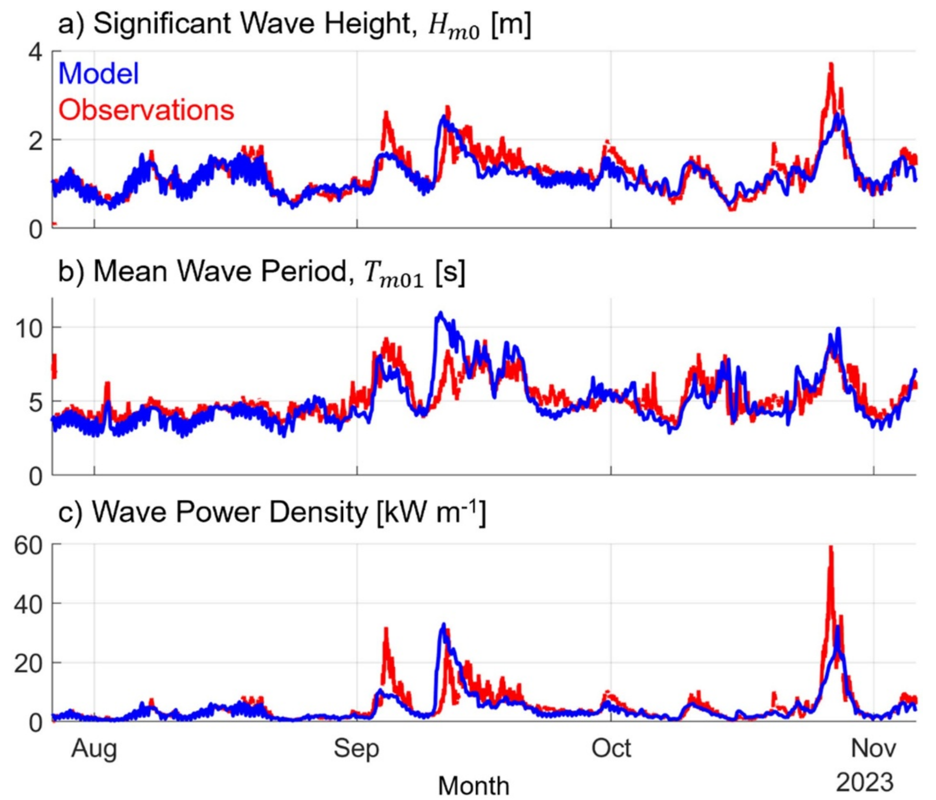

Figure 5. Model (blue) versus observed (red) significant wave height, H_{m0} (a), mean wave period, T_{m01} (b), and wave power density (c), over the duration of the Sofar Spotter buoy deployment (x-axis).

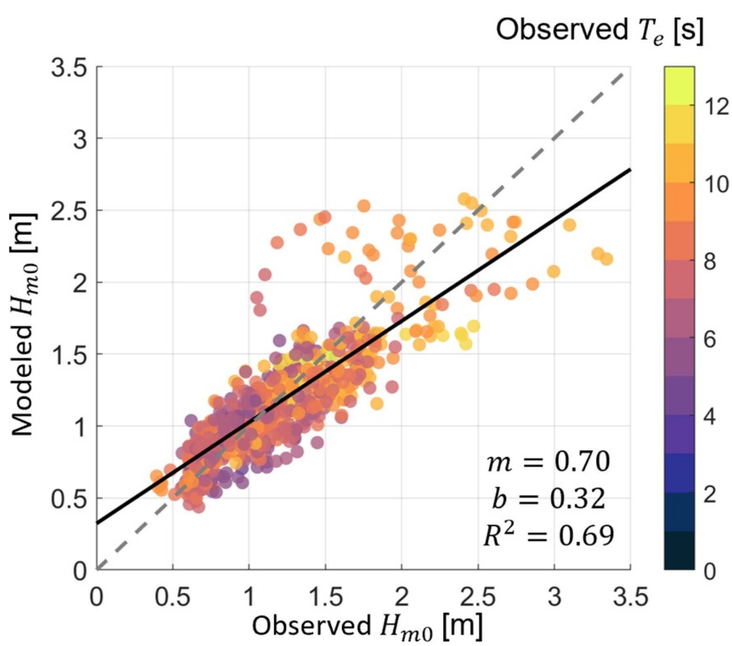

Figure 6. Modeled (y-axis) versus observed (x-axis) significant wave heights (H_{m0}) for each measurement of the deployment period. Colors indicate the observed wave energy period (T_e). Linear regression best fit for wave heights is given as a black line with slope (m), y-intercept (b), and goodness-of-fit (R^2), provided in the bottom right. A 'perfect' 1:1 ratio is shown as a dashed gray line.

Table 2. Mean wave power density (kW m^{-1}) for August, September, and October from the 2023 observations, 2023 CARICOOS nearshore wave model (CNWM) model, and 41 year hindcast model.

	August	September	October
2023 Observations	3.5	10.6	8.0
2023 CNWM model	2.5	6.8	4.8
41 Year model	3.4	5.3	5.7

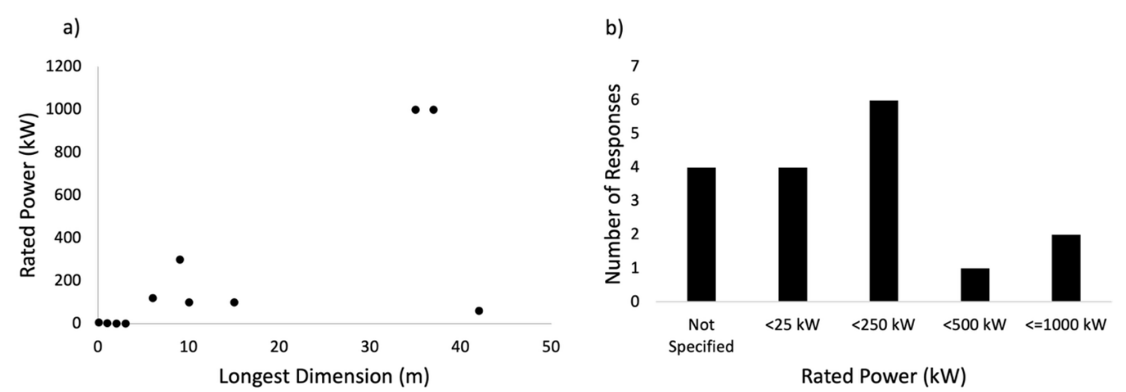

Figure 7. Dimensions (a) and rated power (kW) (b) of the wave energy devices included in the request for information responses.

4. Discussion

The spatial analysis reveals the geographic limitation of suitable wave energy resources for powering offshore IMTA off Puerto Rico and the USVI. While several locations exhibit sufficient wave energy (>5 kW m^{-1}), this remains the most limiting parameter for feasibility. Seasonal variability of wave energy resources was not limiting. Despite lower wave energy levels in this region compared to other parts of the US (Yang *et al* 2023), it is considered sufficient for powering low-demand, off-grid operations like offshore IMTA (Davonski 2024). Key considerations for wave energy to power aquaculture include daily and seasonal energy variations and the need for energy storage to assure consistent power. This aligns with Garavelli *et al* (2022) who found viable wave energy resources for powering offshore aquaculture in specific areas off the coast of California and Hawaii, despite seasonal constraints. With seasonal energy variations, storage would be recommended and would likely take the form of batteries, similar to the ones incorporated in oceanographic buoys that can generate their power from renewable energy (Cavagnaro *et al* 2020). Ultimately, the viability of the resource hinges on the intersection of availability, technology development, energy demand, and energy storage.

By combining key parameters for co-locating offshore IMTA and wave energy, potential suitable areas with the highest suitability score (19.5) were identified off Puerto Rico and the USVI: northwest Puerto Rico, northwest Culebra, east of Vieques, and north of St. Thomas in the USVI. Mean annual wave energy resources ranged from 5.1 to 17.4 kW m^{-1} in these areas. In northwest Puerto Rico, suitability was limited by the presence of underwater cables, navigation routes, critical habitat of marine species, hard bottom benthic habitat, and marine protected areas. Off the coast of Culebra, suitability was constrained by vessel traffic, marine protected areas, and danger-restricted areas. Off Vieques, key limitations included marine protected areas, critical marine species habitats, and coral reefs. Off St. Thomas, constraints stemmed from submarine cables, navigation routes, and bathymetry. The potential suitable areas identified in the spatial analysis with lower suitability scores can still be considered for co-location, but have more limitations (e.g. higher bathymetry, navigation routes more frequented, more protected areas) than the areas with high suitability scores, which would make the planning of a co-located project more challenging. Any area containing a parameter with a suitability score of 0 in our analysis is considered as a no-go zone. For example, a site with a fish aggregating device should be excluded.

Although the spatial analysis performed in our study allows for the identification of suitable areas for co-location, further assessment will be needed to move towards a co-location project and select a specific site. For example, community engagement will be key to identifying local uses that are not represented in publicly available data, such as areas most heavily fished. In Puerto Rico, nearly all nearshore waters (state jurisdiction from 0 to 9 nm) are used for commercial fishing, with the exception of protected areas, and catches are typically reported by landings (Tonioli and Agar 2011). Thus, understanding how fishing grounds are used requires direct input from the community. Also, understanding the permitting processes for co-location will be required in any selected area, and environmental monitoring (similar to the one performed in our study) will help validate data from models (e.g. wave height) and characterize local environmental processes.

Our study is the first to identify suitable areas for co-locating offshore IMTA and wave energy at a regional scale in Puerto Rico and the USVI. At the global scale, previous studies have assessed the broader feasibility of establishing blue economy industries. By integrating social aspects, economic viability, and environmental sustainability, Cisneros-Montemayor *et al* (2021) identified nations with strong potential for sustainable ocean-based industries (e.g. aquaculture, ocean energy, fisheries, ecotourism, and blue carbon sectors). Their analysis highlighted the Americas, particularly coastal regions, as highly suitable for blue economy development. Within this context, the Caribbean stands out as environmentally suitable for aquaculture, although it remains underdeveloped in the region (Oyinlola *et al* 2018).

While spatial analysis is commonly used for co-location studies (Garavelli *et al* 2022, Ewig *et al* 2025), site-specific data are often lacking, and modeling can be used to predict co-location opportunities (Gonzales *et al* 2024). Our study addressed this by combining model-based spatial analysis with environmental monitoring for site-specific validation to evaluate the potential to co-locate offshore aquaculture and wave energy off the coast of Puerto Rico and the USVI. To assess local wave energy potential, a site offshore of Culebra was selected. The instrumentation package developed for our environmental monitoring campaign successfully measured wave heights and wave periods for three months, allowing estimation of the wave energy resource. Observed wave energy was higher than model predictions during the same time period, likely due to storm activity in 2023. Overall, wave energy data were comparable to the model predictions, showing the usefulness of fine-scale environmental conditions from wave models to assess the feasibility of co-locating offshore IMTA and wave energy. Longer-term monitoring may be necessary to determine whether the observations are comparable to the model across multiple seasons. In our study, we selected the Spotter buoy to evaluate its ability to characterize the wave climate in potential suitable co-location areas. It provided finer spatial scale wave data than models, making it a valuable technology for this case study. Although our study did not collect current data, such measurements would aid in future design and planning.

Although the spatial analysis and environmental monitoring campaign highlight the technical feasibility of co-locating offshore IMTA and wave energy in the US Caribbean, further assessment is needed before implementing a co-located project. Through the request for information, wave energy companies demonstrated their interest in this market and the information provided on wave devices showed the feasibility of a pilot deployment in the near term. Because the Puerto Rico and USVI region is often exposed to hurricanes and tropical storms, wave energy devices and aquaculture net pens will need to be specifically designed for severe climate conditions, like for example having the capacity to submerge (Arena *et al* 2015, Chu *et al* 2023). Future research efforts should address the integration of wave energy and aquaculture systems and identifying key aquaculture species to include species-specific environmental parameters at the local scale (e.g. dissolved oxygen, temperature) in the spatial analysis. A sensitivity analysis of the suitability scores selected in our spatial analysis would also help evaluate the robustness of the identification of suitable areas. Because offshore operations are subject to elevated safety risks due to their exposure to high-energy and open-ocean conditions, a co-located project could increase costs and present additional difficulties in obtaining insurance (Schultz-Zehden *et al* 2018).

In the US Caribbean, there is no permitting regime specific to aquaculture or marine energy, which may present additional challenges for co-location. This should be further explored and may include using established frameworks from other US states for each industry (e.g. Pacific Energy Ventures LLC & Pacific Northwest National Laboratory, 2020 for marine energy) or international co-location deployments (Freeman *et al* 2022). Understanding the regulatory context for any co-location project will be key to navigating the permitting process and to the overall project success. While this study assessed the technical aspects of co-location, understanding community perspectives and social license will be essential for project acceptance, especially in the US Caribbean (Kelly *et al* 2017, Brugere *et al* 2023, Trueworthy *et al* 2025). Working with stakeholders and local communities to define how co-location is feasible throughout the US Caribbean will be necessary, including the size and scale of a potential project and possible community benefits such as jobs (Gonzales *et al* 2024). Co-located projects will need to be in line with community values and are likely to be more successful if they are community-led or championed by the community.

5. Conclusion

This study presents a real-world assessment of the suitability of co-locating offshore aquaculture and marine energy—specifically IMTA and wave energy in the US Caribbean. It advances understanding of aquaculture and marine energy co-location, a relatively unexplored area. Combining key parameters, the spatial analysis identified potential suitable areas for co-location off the coast of Puerto Rico and the USVI. Wave energy resources measured at a representative suitable site reveal that the resource is sufficient to power aquaculture and is comparable to model predictions. Through the combination of spatial analysis, environmental monitoring, and information on wave energy device readiness, several key components for the technical feasibility of co-location have been demonstrated in the US Caribbean islands.

Next steps toward real-world viability include addressing potential challenges such as permitting, cost-effectiveness, and environmental effects. For example, a demonstration project would be a useful pathway forward to generate operational data (e.g. wave energy output, energy use, and storage needs) and environmental data (e.g. water quality, noise levels), which can support social acceptance and inform permitting processes, as well as to confirm technical aspects of co-locating aquaculture and marine energy (e.g. mooring design, interactions between a wave device and IMTA system, integration, energy storage systems). The evaluation of the technical and economic feasibility of wave-powered offshore aquaculture operations would also inform the cost-effectiveness of a co-located project. While progress has been made towards the co-location of aquaculture and marine energy, these remaining gaps and challenges need to be addressed to create successful co-located projects.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://mhkdr.openei.org/submissions/545.

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