

Coastal and nearshore aquaculture: Assessing energy use and application of renewable energy resources

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ABSTRACT

This study examined the energy requirements of shellfish (oyster and geoduck) and finfish (sablefish) production in nearshore and coastal aquaculture facilities in Washington State and Hawai'i and assessed the potential for meeting those requirements with renewable energy technologies such as marine, solar, and land-based wind energy. The energy consumption of the various aquaculture operations was calculated through energy models built based on data collected through site visits and operator interviews. The total annual energy use per million shellfish seeds was 15,298 kWh, and the energy use per thousand finfish was 64,420 kWh. Major drivers of energy use were found to be the production of algae, rotifer, and artemia to feed the shellfish and finfish, the processes required to sustain finfish broodstock, and the pumping energy required for seawater distribution. The resource potential and ability to power operations from marine, solar, and land-based wind energy were evaluated for each site. It was determined that tidal energy is not viable at the Washington State locations studied. Solar energy and land-based wind energy are more viable and may be able to offset part, and in some cases all, the energy needs at the sites studied. Opportunities remain for analyzing how the implementation of energy efficiency measures could change the energy use profile of the aquaculture operations at each facility. This research found that renewable energy could provide a reliable source of power for aquaculture operations.

1. Introduction

With the human population increasing, the need to produce protein grows and aquatic food plays an important role in food security and global supply (Costello et al., 2020; FAO, 2024). The aquaculture industry has experienced long-term, regular growth since 1950 and is currently experiencing record growth worldwide; in 2022, aquaculture even surpassed wild-capture fisheries in terms of overall production (FAO, 2024). In the United States (U.S.), the number of aquaculture farms and total sales has been consistently growing over the past few years (FAO, 2024). While the U.S. is still behind in global aquaculture production (National Oceanic and Atmospheric Administration, 2025), it aims to restore competitiveness and increase seafood production (*Executive Order No. 14276 Restoring American Seafood Competitiveness*, 90 FR 16993, 2025). Aquaculture operations can take many forms, ranging from inland farms that rely on ponds and recirculating systems to offshore operations that occur in marine environments further from

the coast. A common type of aquaculture operations is coastal aquaculture, which refers to operations that occur in the coastal sea ranging from the coastline to the adjacent exclusive economic zone, and mostly refers to nearshore environments (Buck et al., 2024). Nearshore aquaculture encompasses operations that occur in the immediate vicinity of the coast (Buck et al., 2024). Offshore and nearshore aquaculture are commonly referred to as marine aquaculture in the literature (Buck et al., 2024). Combined, offshore, coastal, and nearshore aquaculture represented a little more than half of the global aquaculture production in 2022 compared to inland aquaculture (FAO, 2024).

Although a promising industry for feeding the world's population, aquaculture has historically experienced challenges related to the perceived environmental effects of its operations. In recent years, the industry has been adopting new practices centered around more effective siting and improved management (Naylor et al., 2021), but other aspects, such as the energy requirements and supply options, have received less attention. Energy needs for aquaculture operations can

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vary greatly by species and type of operation (Pelletier et al., 2011) and can include uses such as lighting, feeding, pumping, aeration, processing, monitoring, transportation, and others (Freeman et al., 2022). Research has been initiated to understand the energy requirements of aquaculture operations and investigate the potential for powering them with renewable energy sources, such as marine energy (energy from waves, tides, ocean currents, or salinity and temperature gradients), solar energy, or wind energy (Freeman et al., 2022; Stockbridge et al., 2025; Weiss et al., 2018). While much of the focus has been directed towards offshore aquaculture (Garavelli et al., 2022; Clemente et al., 2023; Ewig et al., 2025), nearshore and coastal aquaculture also present interesting opportunities for co-location with renewable energy sources. Co-location is the sharing of space and/or resources, and for these purposes also providing power to aquaculture operations (Garavelli et al., 2022). This research attempted to identify opportunities for co-location with current aquaculture facilities but focused on availability of renewable energy resources nearby facilities rather than limiting potential sources to those that could be specifically integrated and co-located.

This research focuses on understanding how renewable energy could reliably power remote and nearshore or coastal aquaculture, with a focus on tribal aquaculture operations. Many cultures have historically relied on forms of nearshore and coastal aquaculture that can take place in a variety of locations and can vary in scale and cultivation practice based on the communities they serve. Indigenous aquaculture, rooted in traditional knowledge and place-based observations of Native communities, strengthens local seafood production as part of subsistence and/or cultural practices thereby maintaining connection and ability to harvest traditional and customary foods (Ridlon et al., 2021; Costa-Pierce, 2022).

The Jamestown S'Klallam Tribe (JST) in Washington state manages coastal and nearshore aquaculture facilities in both Washington and Hawai'i. Cultivation and harvest of fish and shellfish have been integral to the S'Klallam way of life for thousands of years. JST first established shellfish farming operations in the early 1990s to renew the practices of their ancestors and preserve culturally important resources for subsistence and trade. Today, under the name of Jamestown Seafood, JST aims to protect and share ancestral fish and shellfish resources while ensuring continued economic growth sustainably. This commitment to sustainable aquaculture, including a progressive goal of net-zero carbon emissions by 2032, in part by making tribal-owned operations energy efficient or energy neutral, motivated JST to partner on this research study. Aligned with JST's aquaculture development and sustainability goals, this research aimed to assess the ability to use renewable energy resources for their operations. While this research focused on JST's aquaculture operations, the methods may also be applied to any aquaculture system. The process for performing the energy assessment remains the same for aquaculture sites of varying operational characteristics.

A key step in evaluating the potential for renewable energy to power aquaculture is understanding the specific energy needs of the various aquaculture processes and facilities involved in these operations. However, the literature shows that data on the energy requirements of aquaculture operations are very limited (Freeman et al., 2022; Zoli and Bacenetti, 2025; Klatt et al., 2026). To help fill this gap, particularly in the U.S. as aquaculture operations grow, this study assessed the energy needs of coastal and nearshore aquaculture operations and evaluated the potential for renewable energy to provide power. The energy needs assessment focused on JST's shellfish and fish production at four aquaculture facilities. For each facility, energy uses were identified, and the energy consumption was estimated. The renewable energy resources were estimated for marine, solar, and land-based wind energy at each location and their potential to provide power to aquaculture operations was assessed, including the percentage of energy use that could be offset by each different technology.

2. Methods

The energy consumption of coastal and nearshore aquaculture activities at JST facilities was assessed and the potential for meeting those energy needs with renewable energy sources was identified. First, data were collected about the sites and the type of equipment used at each facility, then energy models were developed using simulation software and other relevant calculations to estimate the overall energy consumption. The feasibility of energy generation with marine energy, solar energy (specifically solar photovoltaic), and land-based wind energy for each aquaculture facility was also assessed by evaluating the resource potential for each type of energy. The estimated energy consumption of aquaculture operations was compared with the available renewable energy resources. This comparison was used to identify which type of renewable energy could power JST aquaculture operations.

2.1. Aquaculture sites

This study focused on four coastal facilities where JST maintains aquaculture operations. Three of these facilities are in Washington and one is in Hawai'i. The Point Whitney Shellfish Laboratory (PW), John Wayne Marina (JWM), National Oceanic and Atmospheric Administration's (NOAA) Manchester Research Station (Manchester Station) are in Washington and the Natural Energy Laboratory of Hawai'i Authority (NELHA) Hawai'i Ocean Science and Technology (HOST) Park is on the Island of Hawai'i (Fig. 1).

JST's aquaculture activities are centered around juvenile oyster (seed) production (*Magallana gigas*, formerly *Crassostrea gigas*, and *Magallana sikamea*), juvenile geoduck (seed) production (*Panopea generosa*), and sablefish (*Anoplopoma fimbria*) production and research. Oyster and geoduck seed production are conducted at NELHA, PW, and JWM, while sablefish production and research are conducted exclusively at Manchester Station.

The oyster production process begins at NELHA where most of the oyster seed are produced. NELHA is a State of Hawai'i Government Agency focused on research into sustainable energy, aquaculture, and other ocean-related fields (Natural Energy Laboratory of Hawai'i Authority, 2025). NELHA's HOST Park, where JST maintains its hatchery, is located on the Kona coast of the Island of Hawai'i. JST's NELHA hatchery facilities include an office and laboratory where microalgae cultures are started, agricultural greenhouses with algae production equipment, upwellers, and an ozone generator. The NELHA site produces approximately 51 million oyster seed per year that are then transported to Washington for managed grow-out at the PW and JWM sites. A key component of operations at NELHA is algae production for oyster feeding. Algae production starts in the laboratory building before being transferred to grow tanks or specialized algae growth systems in agricultural greenhouses where they grow until ready for feeding. Oysters are started at the hatchery and moved to nursery upwellers where they continue to grow until they reach a size of 2.4 mm and are sent to the PW site.

The PW Shellfish Laboratory is located along Dabob Bay within the Hood Canal basin of Washington's Puget Sound. The site is owned by the Washington State Department of Fish and Wildlife and leased to JST for its aquaculture operations. JST's facilities include a workshop, laboratory, office, algae production buildings, two greenhouses, a spawning/setting building, and oyster processing and shipping buildings. The site also has a saltwater pond that under certain conditions produces algae that is suitable for oyster feeding. The operations at PW center around algae production, oyster and geoduck production and grow-out, and processing of adult oysters harvested from the farm tidelands in Sequim Bay. Algae are produced year-round to feed the oysters and geoducks. Algae production starts in small volumes in the laboratory before being transferred to an intermediate algae building to increase in size and concentration utilizing culture vessels from 1 L to 200 L in volume. The algae are then transferred to tanks in two greenhouses where they grow

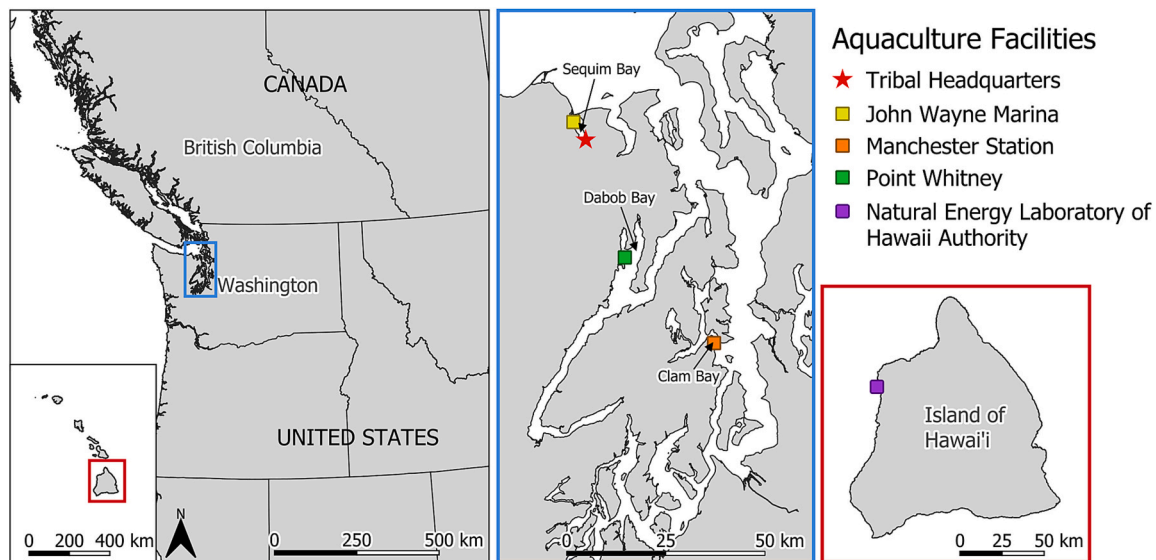


Fig. 1. Locations of the Jamestown S'Klallam Tribe aquaculture facilities in Washington (inset outlined in blue) and Hawai'i (inset outlined in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for approximately four or five days until they are ready for feeding. Production of geoduck seed is conducted entirely at PW where geoduck broodstock are spawned in the site's spawning and hatchery building. Geoduck larvae are transferred to nursery upwellers where they undergo settlement and grow until 6 weeks old. The geoduck seed are then transferred to nursery raceway tanks and grown until ready to be sold or transferred to tribal tidelands for planting at 4.5–9 mm in size. JST produces up to 3 million geoduck seed per year. Oysters received from the NELHA site are raised in the spawning and hatchery building and nursery upwellers at PW. Upwellers boost the oysters to a larger size (2.4–5 mm) before they are either sent to JWM to grow further in Floating Upweller Systems (FLUPSYs), or they are packaged and shipped directly from PW to companies who purchase the oyster seed at a smaller size.

JWM is located on Sequim Bay in Washington off the Strait of Juan de Fuca. JST leases a dock at the marina to house its FLUPSYs and oyster seed sorting equipment. Oyster seed growing at JWM are transferred daily from FLUPSY bins to a sorting machine that groups them by size. Once they reach 6–12 mm in size they are either sold or transferred to farms where they will grow into adult oysters for selling. Adult oysters harvested from the Tribe's farmed tidelands at PW are processed, packed, and shipped in the processing and shipping facilities.

NOAA's Manchester Station is a marine culture and experimental research station located on the shores of Clam Bay in Puget Sound. JST has a research partnership with NOAA and its facilities at the Manchester Station site that consists of a single building and nearshore in-water net pens. JST's sablefish operations happen entirely at the Manchester Station site. Sablefish farming and research operations at Manchester Station are primarily concentrated on broodstock storage, spawning and hatching, feed production of artemia and rotifer (*Rotifera* spp.), and larval rearing. Sablefish production begins in the broodstock area, where adult broodstock sablefish are stored in tanks for the purpose of spawning. The fish stay in the spawning tanks for one to three months, where the incubation process occurs. After the eggs hatch, juvenile sablefish are relocated to tanks where they will be reared and fed using rotifer grown on site for three to four months. As sablefish approach adulthood, they are relocated to either large, outdoor tanks or net pens located in the bay until they are harvested. JST produces between 10,000–11,000 sablefish annually at Manchester Station, with each fish averaging around 2.3 kgs.

2.2. Site operational characteristics

Each site included in the study has different equipment and operational characteristics that were considered for the energy assessment. All sites are active year-round but the peak oyster growing season is May through October, and production is reduced outside of that timeframe. Geoducks are typically only grown between December through June. These differences in growing season and production levels were documented to assess any seasonal variations in energy consumption across the four sites.

One of the NELHA's key features is its ability to use the temperature differentials found in tropical environments and bring cool deep water and warm surface water from the ocean for aquaculture operations (HOST Park, 2025). The system provides sufficient pressure for JST to use the water directly, eliminating the need for local pumps. In addition, the average deep seawater temperature of 7 to 8 °C and the average surface seawater temperature of 26 °C are ideal for oyster and algae production respectively, removing the need for supplemental water heating or cooling. The site also has an abundance of natural light that is well-suited for algae growth. The laboratory contains lighting, space cooling, and additional plug loads to support algae growth. The agricultural greenhouses for algae production are open-sided structures covered by a cloth shade, allowing the use of sunlight and avoiding grow lights. The algae tanks and the specialized algae growth systems rely on aeration pumps. Submersible pumps are used to move algae between the tanks in the greenhouses and for feeding the oysters in the hatchery and the upwellers. The water in the oyster hatchery and nursery upwellers is filtered through an ozone filtration system.

Like NELHA, PW also relies on seawater supplied by central seawater pumps but requires additional, local pumps to distribute the water throughout the site. Water runs through UV filters and, in some cases, pasteurization before being used for algae production or oyster and geoduck grow-out. Once the oyster seed arrive from NELHA to PW, they continue to be fed algae grown on site. Algae cultures are started in large tubes in the laboratory that use LED lighting and blowers for aeration. When ready, the algal cultures are transferred first to an intermediate algae building where cultures are grown up in concentration. They are then transferred to tanks and specialized algae growth systems in two greenhouses on site. Both the tanks and the specialized systems have LED lighting and aeration. Water heating systems are used to heat the filtered seawater to a suitable temperature for algae production.

Submersible pumps are used to move the algae between tanks to either the hatchery or the nursery upwellers. Under certain conditions, algae naturally growing in the site's seawater pond may be used for feeding.

Once the oyster seed at PW have reached a sufficiently large size, they are sent to the FLUPSYs at JWM for continued growth and size-selective sorting. These systems consist of floating structures with containers through which seawater is circulated via submerged pumps. The location of the FLUPSYs in Sequim Bay allows for the oysters to be naturally fed as they grow. A sorting machine is used daily by JST staff to check oyster sizes and determine whether they are ready for sale or require further grow-out.

At Manchester Station, new sablefish broodstock is captured annually and stored year-round in outdoor, covered tanks. Seawater for the tanks is provided by the site's central seawater distribution system. The water runs through UV filters and a chiller to cool from 8 to 11 °C to approximately 5 °C before being supplied to the broodstock tanks. Two semi-recirculating water systems operate year-round to distribute water through the tanks. The broodstock remain in these tanks except for during spawning periods, which occur for about 3 months each year (typically January through March). Spawning eggs are collected manually and placed into incubation tanks, where the water is gradually increased in temperature to encourage hatching. The hatchery space has little lighting and is maintained at a temperature of 7 °C during the hatching period. Once larvae are hatched, they are moved from the hatchery tanks to the larval feeding and rearing tanks. Rotifer and artemia are produced in a separate space to feed the fish and larvae. The feed is produced in a continuous culture that relies on water heaters to maintain the water temperature around 24 °C. The hatchery, larval feeding, and feed production processes have dedicated pumps for water circulation, UV filters, and blowers for aeration. As they grow, the juvenile sablefish are weaned onto a commercially available prepared diet and placed in a mix of covered and uncovered outdoor tanks. These tanks have a dedicated pump for filling them with seawater from the central distribution system. When they reach a sufficient size, some sablefish are moved to net pens located in the bay at the end of Manchester Station's pier, where electric fencing helps deter predators.

2.3. Energy assessment

The energy consumption for each facility was estimated using operational characteristics, utility bills, existing site reports, and site visits. In-person visits were conducted at PW, JWM, and Manchester Station to gather equipment information. Site visits consisted of building and aquaculture operation walkthroughs with JST site staff. On-site data collection included taking notes and photos of equipment and processes. Information for NELHA was obtained remotely through on-site staff. Utility consumption billing data were obtained for the PW and NELHA sites. Billing data were not available for Manchester Station and JWM.

The building, equipment, and operational characteristics obtained through data collection were used to create an energy use model. The model was created using a combination of energy simulation through the Federal Energy Decision System (FEDS) software and engineering calculations. FEDS is a building energy simulation and analysis software developed by the Pacific Northwest National Laboratory that facilitates the evaluation of energy use and energy efficiency opportunities in buildings (Dahowski et al., 2020; Dahowski, 2021). FEDS was used to model the lighting, space heating, and space cooling for the facilities while engineering calculations were used for specific energy end uses such as water heating, water cooling, pumping, and aeration. Where actual equipment characteristics or operations were not available, assumptions were derived from information from site staff.

Energy use for each aquaculture process and energy end use was estimated for each site. "Process" refers to the activity occurring at the site (e.g., seawater distribution, oyster processing, etc.), while "end use" refers to the purpose of the energy use (e.g., pumping, lighting, etc.). A list of processes by site, general description of each energy end use, and

examples of associated equipment included in this study are provided as Supplementary Material. Energy intensity for geoducks, oysters, and sablefish was estimated by using average weights and annual production rates provided by JST. The average weight used for sablefish was 2.3 kg. The average size of an oyster seed was estimated at 3 mm and based on this 0.07 g was used as the average weight. The average size of a geoduck seed was estimated at 4 mm and based on this 0.016 g was used as the average weight. It should be noted that due to high variability in oyster and geoduck seed sizes, JST does not typically track production by weight; so while the average weights make energy intensity estimates informative, they should not be taken as exact values without further study. Because oysters and geoducks share several processes, a ratio of annual oyster production to annual geoduck production was used to allocate energy use at NELHA, PW, and JWM to each species.

In addition to energy intensity, another calculation was performed to allocate JST's total energy use to each feed species and end product species. While the energy intensity calculation included the energy used to grow feed species within each end product species, this allocation keeps feed species energy use separate. This allocation was calculated by totaling energy use from each process associated with the respective feed species or end product species. Processes that were shared by both feed species and end product species, such as seawater distribution, were excluded from this calculation.

2.4. Renewable energy assessment

An assessment of annual generation potential for marine, solar, and land-based wind energy was conducted for the four JST facilities: NELHA, PW, JWM, and Manchester Station.

2.4.1. Marine energy resources

A marine energy resource assessment was performed to understand the feasibility of marine energy to power JST's aquaculture operations. In Washington, the marine energy resource was focused on tidal energy because ocean waves become quickly attenuated at the mouth of the Strait of Juan de Fuca (Yang et al., 2018), therefore the main marine energy resource available nearby JST's facilities is tidal currents. The tidal energy resource was characterized using a high-resolution unstructured model of the study area executed using the Finite-Volume Community Ocean Model (FVCOM). The model was used to simulate tidal hydrodynamic conditions for the year 2015 and was validated against tide and current gauge measurements in accordance with the International Electrotechnical Commission Technical Specification (IEC-TS) (Yang et al., 2021). Model results of current speeds were recorded as 30-min time series at every node of the model grid. For this study, these time series were used to compute the annual energy production (AEP) that could be produced by a single tidal energy converter in the vicinity of the three Washington JST aquaculture facilities shown in Fig. 1. The tidal energy AEP calculation is provided as Supplementary Material. The tidal-stream AEP calculated for each location was compared against the total energy needs of JST's operations at that location. Note that unlike other renewable resources characterized in this study, tidal energy availability is generally not affected by seasonal variability, which is why its power potential was estimated annually rather than monthly.

In Hawai'i, the marine energy resource assessment was focused on wave energy and ocean thermal energy conversion (OTEC), as these represent the most promising marine energy resources for the region (Yang et al., 2023; Kim et al., 2021). OTEC is viable as it uses the temperature difference between warm surface water and cold deep water to harvest power from the ocean, which can only be achieved in tropical areas like Hawai'i. OTEC resources in Hawai'i for the NELHA site were inferred from (Park et al., 2025) (see Section 3.2.1). Wave energy is viable off the coast of Hawai'i due to the open coast. Wave energy data offshore of NELHA were derived from multiple nested models around Hawai'i (Li et al., 2021). Using model data, wave energy power outputs were computed, and AEP was calculated for a single-body point absorber

wave energy converter. The wave energy AEP calculation is provided as Supplementary Material.

2.4.2. Solar energy resources

The availability of space for solar energy at JST's aquaculture sites was assessed using site visits and satellite imagery. Open ground spaces, rooftops, and parking areas with carport potential were all considered. Solar energy potential was analyzed using the National Laboratory of the Rockies' PVWatts calculator (National Laboratory of the Rockies, 2024; Dobos, 2014). PVWatts is a web-based tool that estimates energy production of solar photovoltaic (PV) systems. Each identified rooftop or carport area was measured via satellite images to determine the available area (m²). Solar resource data for the selected locations based on latitude and longitude was gathered from PVWatts. Potential array size was calculated using the PVWatts formula:

$$\text{Size (kW)} = A \times G \times \eta \quad (1)$$

where:

- A is the area available for PV panels,
- G is the reference solar irradiance for a single unit of area, and
- η is the efficiency of a PV panel.

A standard module was selected from PVWatts, which has an assumed efficiency of 19%. The reference solar irradiance G for a standard module is 1 kW/m². The resulting PVWatts output provided monthly output (kWh) for each system. The monthly output for each location was compared against JST's total energy use at that location.

2.4.3. Land-based wind energy resources

A high-level land-based wind energy resource assessment was performed to determine if wind turbines were a feasible renewable energy option to power JST aquaculture operations. Potential siting locations were selected at each Washington state JST facility based on satellite image criteria such as available ground area, quality of ground area, and proximity to obstacles. After selecting potential areas, the National Laboratory of the Rockies' System Advisor Model (SAM) (National Laboratory of the Rockies, 2023) was used for the analysis. SAM provides techno-economic analysis of several energy technologies, including wind energy. A variety of standard, small-sized wind turbine sizes ranging from 15 to 100 kW were chosen for the analysis to determine which size would produce the best wind energy match. SAM was run for each site with turbine sizes of 15 kW, 25 kW, 50 kW, and 100 kW, at a height of 50 m. Due to potential space constraints, each analysis was only run for a single turbine at each site, with the understanding that the results can be extrapolated to additional turbines if space becomes available. The resulting monthly output for each location was compared against JST's total energy use at that site.

A different approach was used for the NELHA site, where SAM does not have data for the state of Hawai'i. The Global Wind Atlas (Badger et al., 2024) was used for a high-level determination of techno-economic feasibility. The determination was based on an ideal annual average speed of at least 4 m/s to continue analysis (U.S. Energy Information Administration, 2026). The wind speed at the NELHA site did not meet this criteria and the site was excluded from further assessment.

3. Results

The energy uses for various aquaculture operations and available renewable energy resources were assessed for JST's four aquaculture facilities.

3.1. Energy usage of aquaculture sites

The estimated energy use for each of the four sites is presented by fuel type in Table 1. For each site, only JST's portion of the total site

Table 1

Estimated annual energy use by aquaculture site.

Site	Annual Electricity Use (kilowatt-hours, kWh)	Annual Propane Use (kWh)	Total Annual Energy Use (kWh)
Natural Energy Laboratory of Hawai'i Authority	94,895	0	94,895
Point Whitney	536,364	101,460	637,824
John Wayne Marina	93,388	0	93,388
Manchester Station	708,624	0	708,624

energy use was estimated. The analysis showed that the primary energy source for JST's operations across all four sites is electricity, which consists of 93% of the energy used; only the PW site uses propane for space heating.

The NELHA, PW, and JWM sites have a combined annual energy use of 826,107 kWh. With an estimated production of 54 million oyster and geoduck seeds per year across the three sites, the annual energy use per million shellfish seeds can be projected as 15,298 kWh. JST does not track oyster and geoduck production by weight due to high variability in seed size. However, energy intensity was approximated using average weights of oyster seed and geoduck seed. The resulting estimated energy intensity is 3442.11 MJ/kg for oysters and 786.77 MJ/kg for geoducks.

Based on Manchester Station's annual energy consumption of 708,624 kWh and an estimated production of 11,000 sablefish per year, the energy use per thousand finfish is estimated as 64,420 kWh. The energy intensity for sablefish production is 100.83 MJ/kg, based on an average sablefish weight of 2.3 kg.

Manchester Station is the largest energy user, accounting for 46% of JST's energy consumption, followed by PW, consuming 42%. JWM and NELHA each consumed 6% of the total energy use.

The largest energy end uses for JST's aquaculture activities are pumping and water cooling (38% and 23%, respectively). Lighting and space heating follow at 11% and 9%, and all other end uses are below 10% of JST's energy consumption. The energy consumption breakdown by end use is shown in Fig. 2.

Energy use was also calculated by process area at each site (Fig. 3). The largest energy using process area at NELHA is feed production, which centers around algae production and uses 58% of the total energy. Spawning and hatching use 23%, and seawater distribution uses the remaining 19% of the site's energy. Oyster grow-out in nursery upwellers does occur at NELHA, but there is no energy-use component due to the pressure from the main seawater distribution lines providing adequate flow to the oysters without requiring any additional pumping. The largest energy-consuming process area at PW is also feed production (algae), which uses 59% of the total energy. Grow-out and seawater distribution are also significant energy processes for PW. JWM only has two process areas, oyster grow-out and processing. The bulk of the energy use at JWM is dedicated to moving water through the FLUPSYs during grow-out, accounting for 91% of the total energy use. The remaining 9% is used in the sorting process, where a machine separates oyster seeds by size. Manchester Station's highest energy using process area is the sablefish broodstock, which requires water cooling and accounts for 55% of the site's total usage. The seawater distribution is the next largest process area at Manchester Station, using 20% of energy use for pumping. The remaining 25% of energy use consists of the hatchery, feed production, larval rearing, juvenile nursery, and net pens.

Energy use by species (Table 2) was also estimated by allocating processes to either feed species (algae, rotifer, and artemia), shellfish (oysters and geoduck), or finfish (sablefish). This allocation method excluded all shared processes, such as seawater distribution, to avoid misrepresenting shared energy use. Seawater distribution is estimated to require 225,674 kWh/year across all sites, while other shared energy uses like maintenance facilities require 36,192 kWh/year. Since oyster and geoduck production processes often overlap, the energy use for both

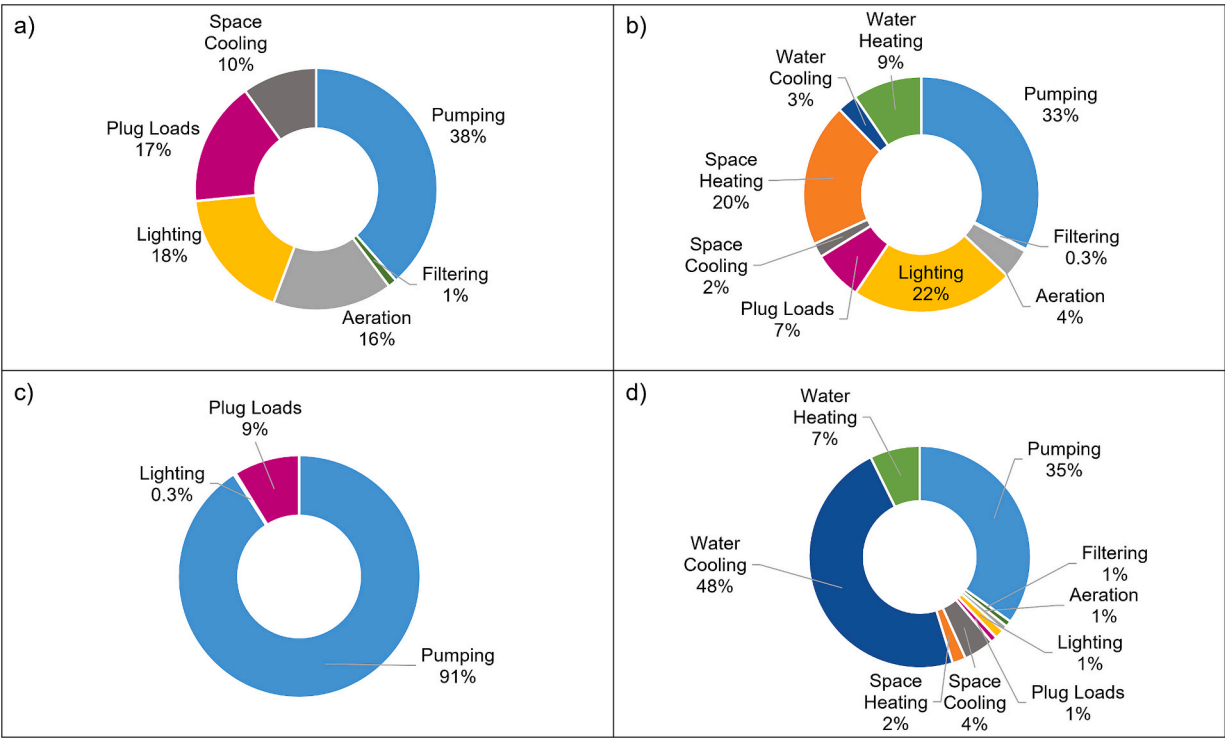


Fig. 2. Estimated total annual energy consumption by end use for Jamestown S'Klallam Tribe sites: a) Natural Energy Laboratory of Hawai'i Authority, b) Point Whitney, c) John Wayne Marina, and d) Manchester Station.

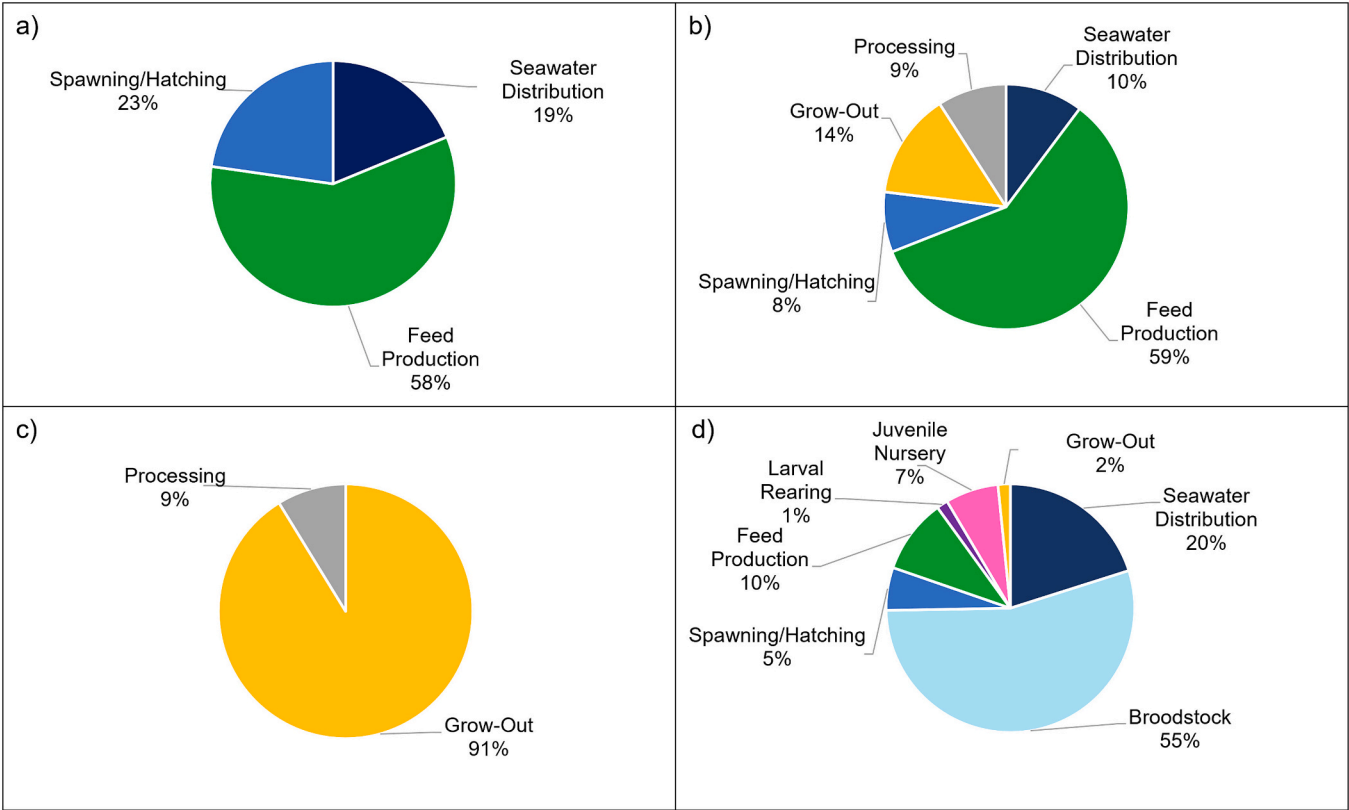


Fig. 3. Estimated annual energy consumption by process for Jamestown S'Klallam Tribe sites: a) Natural Energy Laboratory of Hawai'i Authority, b) Point Whitney, c) John Wayne Marina, and d) Manchester Station.

is accounted for under shellfish and is not distinguished by species. Feed species use a combined 463,154 kWh annually, accounting for 36% of

JST's total energy use.

Table 2
Estimated annual energy use by aquatic species.¹

Species	Annual Energy Use (kilowatt-hours, kWh)	Percentage of Total Energy Use ²
Feed Species: Algae	394,215	31%
Feed Species: Rotifer and Artemia	68,939	5%
Shellfish: Oyster and Geoduck	497,161	39%
Finfish: Sablefish	312,551	25%

¹ Excludes shared processes.

² Shown as a percentage of total energy use excluding shared processes.

3.2. Renewable energy opportunities

3.2.1. Marine energy

To characterize the marine energy resources at each aquaculture site in Washington, the FVCOM 3D tidal speed time-series were used to compute the tidal-stream AEP as described in Section 2.4.1. As mentioned previously, a minimum cut-in tidal speed of 0.5 m/s is considered necessary for power production. Fig. 4 shows representative tidal speed vertical profiles and their corresponding probability of exceedance at each of JST's Washington sites. The probability of exceedance indicates the likelihood that the tidal speed at a particular depth will be exceeded during a full tidal cycle. At all the sites, less than 1% of the tidal flows would be able to engage a tidal turbine. The AEP at each of the sites, assuming the installation of a vertical-axis turbine with a rotor 1 m in diameter and 1 m in height positioned near the surface, are 0.0 kWh at PW, 0.8 kWh at Manchester Station, and 1.8 kWh at JWM. While JWM has the highest AEP, it is still less than 1% of the site's total energy use.

Marine energy resources at NELHA in Hawai'i were also assessed. The wave power off the west coast of the Island of Hawai'i, where NELHA is located, is estimated to be below 5 kW/m year-round. The AEP for a 2 m single-body point absorber wave energy converter is estimated to be 3655.33 kW/h. Park et al. (Park et al., 2025) used a numerical model to characterize OTEC resources in the same region over 10 years (2012–2021), based on a 100 MW OTEC plant. OTEC power is found to be negligible near the coast, up to 84 MW at 500 m depth, and about 130 MW at depths greater than 1000 m. The AEP is estimated to be negligible along the coast and up to 1.2 TWh/year at depths greater than 1000 m.

3.2.2. Solar energy

Potential siting locations for solar arrays were chosen for each site. At NELHA, open ground within JST's lease area is available, so a ground-mounted array was chosen. At PW, open ground spaces are not

available, so solar was only analyzed for the building rooftops and a carport. At JWM, several parking lots are available for carports to house solar arrays. At Manchester Station, several rooftops were analyzed along with a carport and a ground array. Based on the available ground, rooftop, and carport areas and PVWatts analysis, NELHA can house an approximately 750 kW solar array, PW 154 kW, Manchester Station 921 kW, and JWM 86 kW. Fig. 5 shows the solar energy potential compared to each aquaculture site's energy use. For NELHA, the solar energy potential is higher than the site's energy usage year round. It is also higher for JWM and Manchester Station, but only in the spring and summer months. The highest solar AEP is estimated to be at NELHA, followed by Manchester Station, and PW and JWM.

3.2.3. Land-based wind energy

Potential siting locations for land-based wind energy turbines were determined at each site. Siting for wind energy is limited at PW, as many areas are either beaches, which are not ideal because of sand, or too heavily forested. One forested area was selected for a single turbine, but it was noted that trees would need to be cleared to install and operate the wind turbine. JWM has an area north of the marina that has potential for siting a wind turbine. Manchester Station has a large area north of the main campus that could potentially house a wind turbine. The largest turbine size analyzed, 100 kW, matches the energy profile of each site best. Fig. 6 shows the wind energy potential of a 100 kW turbine compared to each aquaculture site's energy use. For each site, the wind energy potential is lower than the energy usage, specifically for PW (Fig. 6a) and Manchester Station (Fig. 6c). The highest wind AEP is found to be at Manchester Station, followed by PW, and JWM.

3.2.4. Renewable energy summary

The summary of AEP for marine, solar, and land-based wind energy compared to annual site energy needs is shown in Table 3. While some technologies have the potential to meet or exceed annual site energy needs on an annual basis, actual coverage varies month to month. With the exception of solar energy and OTEC at NELHA, most sites cannot rely fully on any one of the assessed renewable energy technologies to meet their energy needs at this time.

4. Discussion

The energy assessment results show that there are two interconnected factors affecting energy use in JST's nearshore and coastal aquaculture operations in Washington and Hawai'i: feed production and local environmental conditions. The energy use by species showed that the production of algae, rotifer, and artemia feed for shellfish and finfish

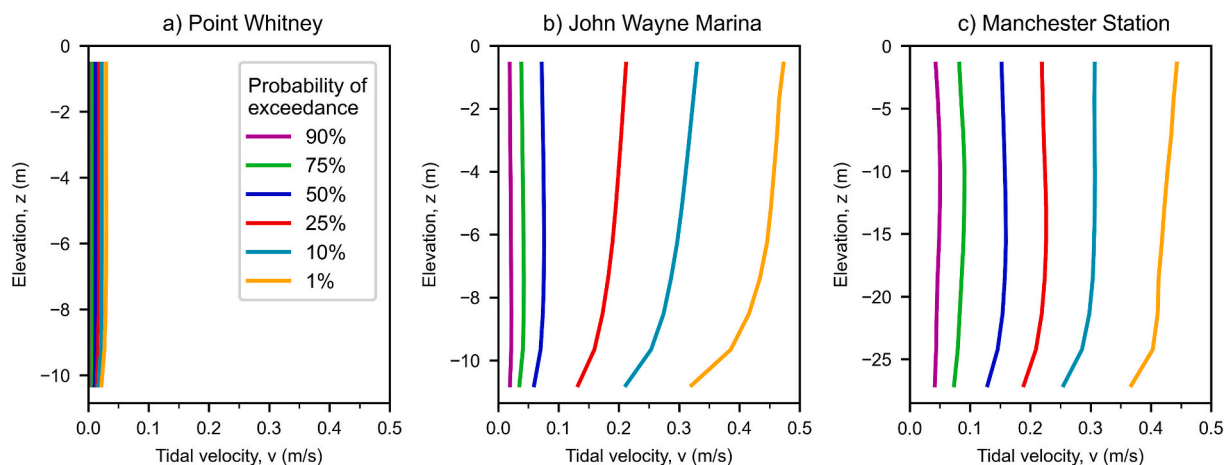


Fig. 4. Tidal speed profiles colored by probability of exceedance at Jamestown S'Klallam Tribe's Washington aquaculture sites: a) Point Whitney, b) John Wayne Marina, c) Manchester Station.

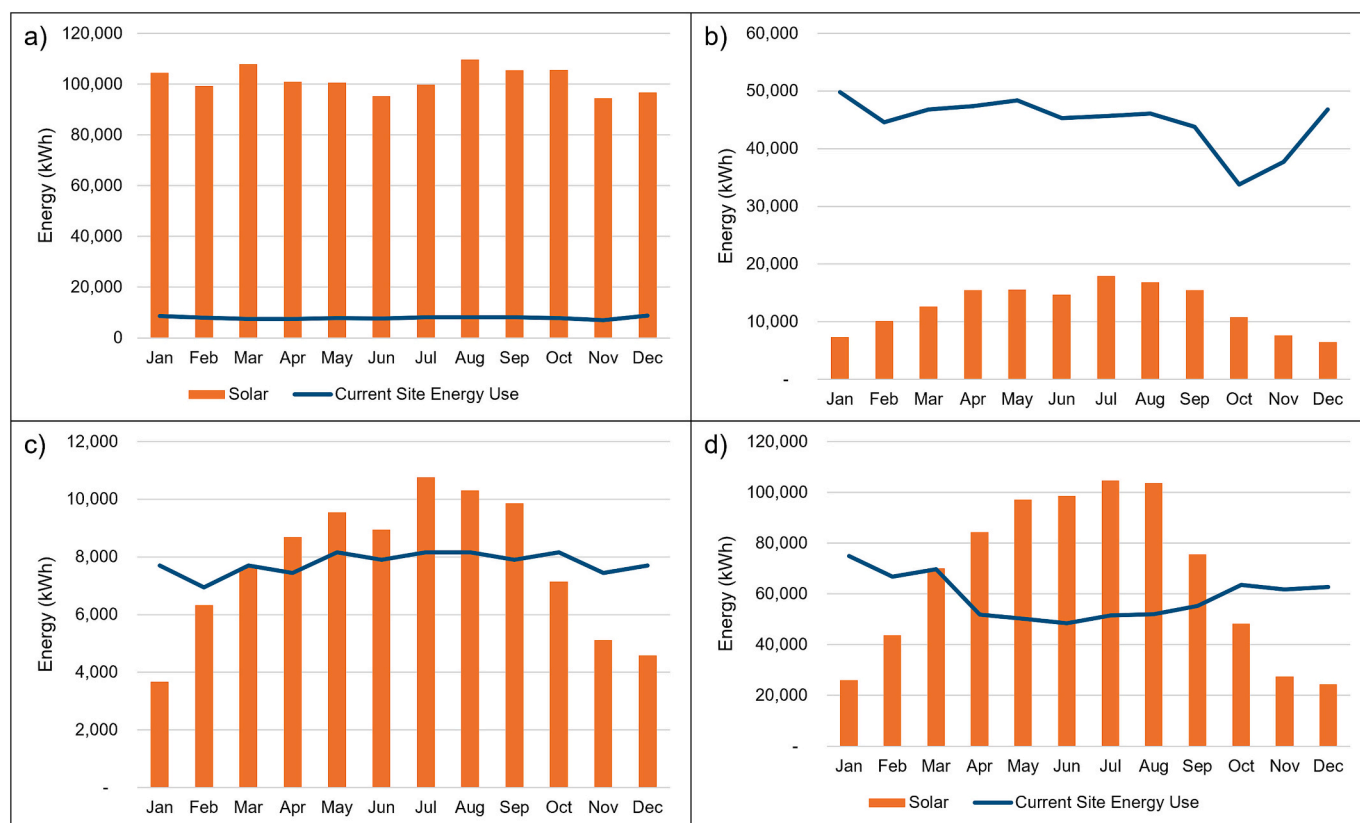


Fig. 5. Solar energy potential compared to site energy usage at a) Natural Energy Laboratory of Hawai'i Authority, b) Point Whitney, c) John Wayne Marina, and d) Manchester Station.

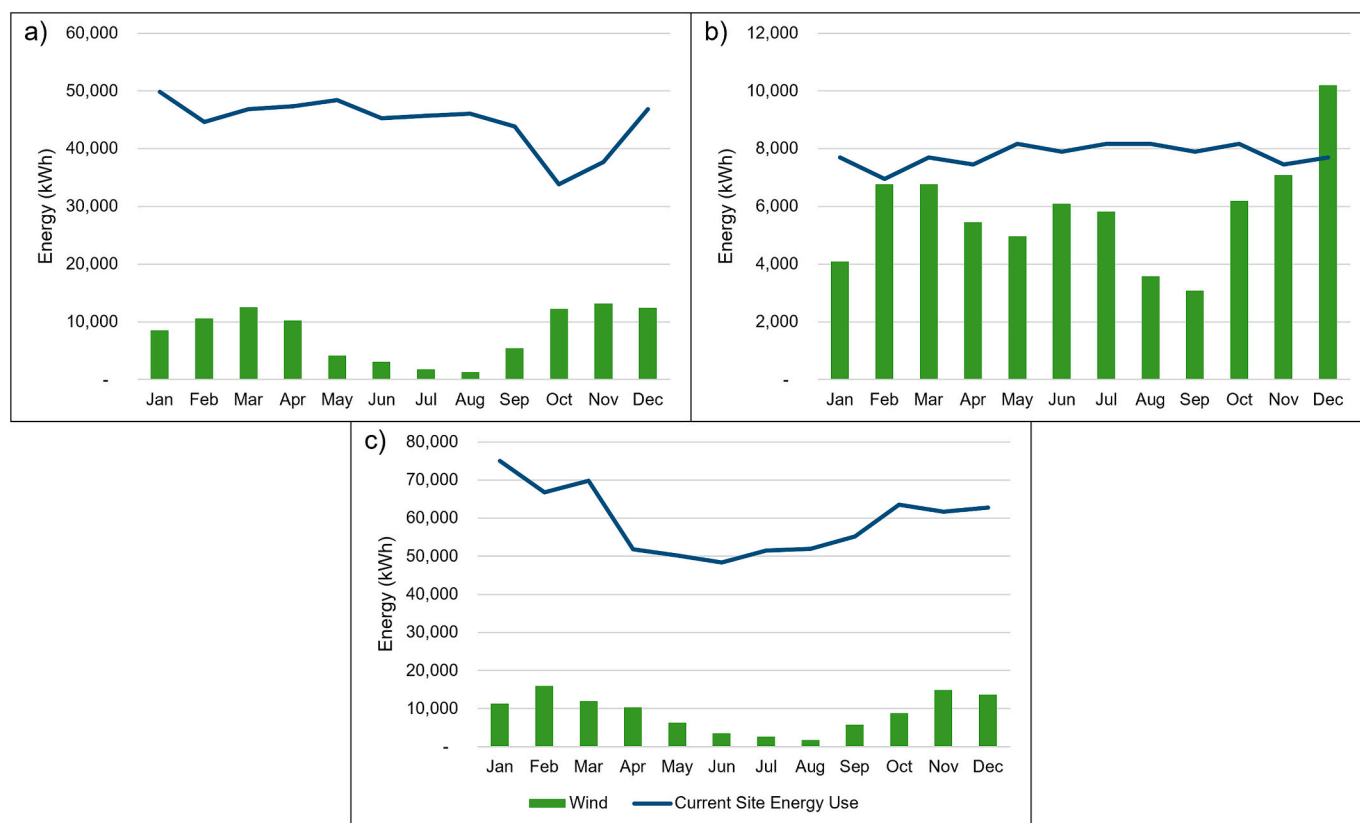


Fig. 6. Wind energy potential compared to site energy usage at a) Point Whitney, b) John Wayne Marina, and c) Manchester Station.

Table 3

Annual energy production at Jamestown S'Klallam Tribe's sites for renewable energy resources.

Aquaculture Site Location	Annual Site Energy Needs (kWh)	Renewable Energy Resource	Annual Energy Production (kWh)	Percent of Annual Site Needs Covered ¹
Point Whitney, Washington	637,824	Tidal	0	0%
		Solar	151,075	24%
		Wind	95,316	15%
John Wayne Marina, Washington	93,388	Tidal	1.8	0%
		Solar	92,629	99%
		Wind	70,063	75%
Manchester Station, Washington	708,624	Tidal	0.8	0%
		Solar	804,157	100% ²
		Wind	106,743	15%
Natural Energy Laboratory of Hawai'i Authority, Hawai'i	94,895	Wave	3655.33	4%
		OTEC	1.20E+09	100% ²
		Solar	1,220,237	100% ²

¹ As compared to annual total site energy use, monthly coverage varies.

² Exceeds 100% of annual site needs.

farming represents 36% of the overall energy use for all species. Algae is used for shellfish feeding, while rotifer and artemia are used for finfish feeding. Combining the energy use of each feed type with the respective species they support shows that shellfish production represents 56% of the overall energy use for all species, while finfish production represents 44%. However, it is important to contextualize these results in terms of the levels of production for each species. JST produces significantly more shellfish by weight than finfish, which suggests that finfish production under the conditions analyzed in this study is more energy-intensive. These results can be attributed in part to differences in the environmental conditions where each species is grown and the ability of each site to leverage local beneficial resources. For example, the NELHA site in Hawai'i is able to sustain algae production and oyster grow-out operations with approximately 15% of the energy required to operate the PW site in Washington, which has similar capabilities of algae production and oyster and geoduck grow-out. This is in large part because NELHA can leverage natural seawater temperatures and sunlight availability for the bulk of its operations. Another example for finfish is the use of the central cold seawater supply at Manchester Station, which is leveraged to reduce water cooling, and therefore its associated energy needs, for sablefish broodstock production. The energy assessment results also highlight a cornerstone of energy use in coastal aquaculture: pumping. At each site, pumping represented between 33% (PW) and 91% (JWM) of total energy use.

The energy needs estimated in this study for coastal and nearshore aquaculture operations of JST in Washington and Hawai'i can be compared with other similar operations in the U.S. or across the globe. However, information about the energy requirements of aquaculture operations is limited in the literature and where available, some data is reported in different metrics (Freeman et al., 2022; Zoli and Bacenetti, 2025) and includes different types of aquaculture operations, species, and energy end uses. This variation in measurement approaches makes it difficult to draw a direct comparison between different types of aquaculture operations. For example, this study found that JST's onsite sablefish production uses 100.83 MJ/kg. Love et al. (Love et al., 2025) found that aquaculture uses on average 122.6 MJ/kg of edible aquatic food, but this varies by species and by different processes and supply chains. More studying using similar metrics and with comparable energy estimates will help to increase the overall understanding of aquaculture energy needs. As the body of literature grows on this topic, future work can include developing a benchmark for increasing the efficiency of operations in terms of energy use.

The assessment of renewable energy production opportunities at all

sites in Washington showed that solar and wind energy are viable sources of renewable energy. With essentially no resource potential for wave energy past the mouth of the Strait of Juan de Fuca (Yang et al., 2019), and less than 1% of tidal flow above the limit needed to operate a tidal energy converter, marine energy is not viable at any of the existing JST aquaculture sites in Washington. While marine energy resources are limited at the current sites, other parts of Puget Sound have been characterized as tidal energy hotspots (Yang et al., 2021) and could potentially be suitable for other existing or future aquaculture operations, such as other tribal aquaculture facilities in the area. Comparing the energy consumption estimates with renewable energy sources, both Manchester Station and JWM have the potential to produce enough solar energy to power the entire site operations during spring/summer months (March – September), but not during late fall or winter months (October – February). PW does not have enough available area to produce adequate solar energy to fully power its operations in any month, with the potential to produce approximately 28% of the site's total annual energy use across all months. PW and Manchester Station do not have enough wind energy potential with the selected turbine to power the full site's energy use. JWM's wind energy potential matches more closely with the site's energy use profile, nearly meeting or surpassing the load requirements in February, November, and December, but falls short in the remaining months. A combination of solar and wind energy may be able to offset 100% of the energy use at JWM, but it would only be sufficient to offset part of the energy use at PW and Manchester Station. While not all of JST's Washington sites can rely solely on renewable energy to power their operations, combinations of wind and solar will still reduce their utility energy consumption and contribute to their sustainability and net-zero carbon emissions goals. As renewable energy technology progresses, or if site-level energy use changes, they may be able to get closer to a fully reliable renewable energy system in the future.

Off the Island of Hawai'i, the availability of marine energy resources was also evaluated. Wave energy is limited on the west coast of the island (Li et al., 2021), and wave energy AEP is found to be lower than the aquaculture energy usage at NELHA. On the contrary, OTEC shows significant potential with AEP estimates reaching up to 1.2 TWh/year (Park et al., 2025). This is approximately 12,000 times greater than the energy demand of JST's aquaculture operations at NELHA. Although an OTEC plant could support these operations, its scale far exceeds their needs and should not be developed solely for this purpose, though OTEC may be appropriate for powering the larger NELHA facility. While wind is not viable at NELHA, a ground solar array has the potential to provide enough energy to meet the aquaculture loads every month of the year.

Copping et al. (Copping et al., 2025) examined the potential for a multi-use OTEC facility at NELHA that would utilize cold, deep ocean water discharged after the OTEC process to cool aquaculture ponds and tanks used for algae cultivation and oyster larvae rearing. They highlighted that the plant could also generate power for aquaculture operations and provide air conditioning for laboratories and other buildings. While this example illustrates an integrated approach to renewable energy use in coastal aquaculture, such efforts remain uncommon elsewhere in the U.S. For instance, Scroggins et al. (Scroggins et al., 2022) estimated that hydropower and solar energy comprise only 5% of direct energy use in catfish aquaculture in Alabama and Mississippi, noting that low energy costs and high energy demands serve as barriers to adopting renewable sources. Challenges for operations from power outages caused by extreme weather events along with goals to transition to sustainable and/or more energy efficient practices could drive greater adoption of renewable energy and battery storage as backup solutions in the aquaculture sector. Further detailing the main incentives for aquaculture operators to switch to renewable energy sources will help better understand this opportunity.

Based on the energy assessment carried out, opportunities exist to implement efficiency measures within current aquaculture operations ranging from variable speed drives for pumps to more efficient lighting

technology. Future steps could include a detailed energy efficiency assessment at each site. This could involve additional testing and evaluation of the systems at each site to identify specific equipment and operational upgrades that would result in energy and cost savings. In addition, the assessment could provide estimates for the capital and operational expenditure for each upgrade or efficiency measure as well as the potential energy consumption and cost savings. Having a more complete understanding of the financial and energy implications of different energy measures could help inform the long-term energy management efforts at aquaculture facilities. Following the energy assessment conducted as part of this study, JST began working with the local electric utility at PW to implement energy efficiency strategies such as heat recovery. The implementation of these measures could enhance the ability of a renewable energy system to meet the site's energy needs.

5. Conclusion

The goal of this study was to understand how electricity and other energy sources are used at four aquaculture sites operated by JST in Hawai'i (NELHA) and Washington (PW, JWM, and Manchester Station) and understand whether resource efficiencies could be achieved by supplying those energy needs through renewable energy sources. An energy assessment of each site was conducted to understand energy consumption by aquaculture process, species, and energy end use. The primary products for the aquaculture operations analyzed are shellfish (oyster and geoduck) and finfish (sablefish), but the sites also produce algae, rotifer, and artemia as feed. The shellfish operations were estimated to consume 826,107 kWh per year, while the finfish operations were estimated to consume 708,624 kWh per year. Feed production represents at least one third of the energy consumption across all sites as this was estimated to consume 463,154 kWh per year. Pumping energy for distributing seawater to the various processes was a major contributor to overall energy use at each site, and was the largest for three out of the four sites studied. In some instances, the sites can limit their energy consumption by taking advantage of synergies between the aquaculture operations and the local environment. Examples of those synergies include using food sources produced naturally in the bays where the sites are located and leveraging sunlight availability and seawater temperature gradients for heating and cooling.

The resource potential and ability to power operations with marine, solar, and land-based wind energy were evaluated for each site. It was determined that tidal energy is not viable at the Washington locations studied and wave energy is not viable at the Hawai'i site. OTEC is a promising resource off the Island of Hawai'i and the NELHA site, including JST's facilities and beyond, could use the power provided by an OTEC plant. Solar energy is also a viable option for NELHA. Solar energy and land-based wind energy are more viable than marine energy for the sites in Washington, and may be able to offset part, and in some cases all, of the energy needs at the sites studied. Opportunities remain for analyzing how the implementation of energy efficiency measures could change the energy use profile of the aquaculture operations at each facility and increase the offset potential from any renewable energy systems on site.

Studies assessing the energy needs of aquaculture operations in the U.S. and beyond are an underrepresented area of coastal and nearshore aquaculture literature. This study contributes to the body of knowledge by identifying energy use for a variety of processes within shellfish and finfish operations at four different aquaculture facilities. Similar studies could increase the ability to comprehensively understand aquaculture energy needs and further assess the feasibility of using renewable energy resources. With the aquaculture industry continuing to grow around the world and within the United States, understanding the energy needs is essential for sustaining operations in the long term. As the body of literature grows, it would be useful to compare aquaculture operations using consistent metrics to understand opportunities for renewable energy. Additionally, a better understanding of energy use will allow us to

project the energy requirements of future aquaculture operations and plan for effective energy supply either through conventional or renewable energy resources.

CRediT authorship contribution statement

Andrea Mengual: Writing – original draft. **Hannah Hudson:** Writing – original draft. **Mikaela Freeman:** Writing – original draft. **Lysel Garavelli:** Writing – original draft. **Fadia Ticona Rollano:** Writing – original draft. **Jim Parsons:** Writing – original draft. **Elizabeth Tobin:** Writing – original draft.

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. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.aquaculture.2026.744233>.

Data availability

Data will be made available on request.

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