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4 Offshore Marine Aquaculture

Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets

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4. Offshore Marine Aquaculture

Key Findings

- Aquaculture is the cultivation of finfish, shellfish, crustaceans, and seaweeds on land or at sea, primarily for human consumption, with additional markets for animal feed and industrial chemicals. The global aquaculture market is projected to be more than $55 billion by 2020 according to the Food and Agriculture Organization (FAO).

- Aquaculture operations can occur in coastal or nearshore zones, and deep-water or offshore areas. Coastal aquaculture is the most predominant form of aquaculture, where pens or fish cages are deployed along the coastline or shellfish and seaweeds are grown on the shallow seabed. Offshore aquaculture operations typically use floating or submersible net pens or cages that are tethered to the seafloor and attached to buoys. There is a trend worldwide to move aquaculture operations further offshore, although the United States has no substantial offshore installations.

- Offshore aquaculture operations require energy to power standard safety, navigation, and maintenance equipment; automatic fish feeders; refrigeration and ice production; marine sensors; recharging of AUVs; hotel power for the crew living quarters (if the structures are manned); and recharging of transport vessels.

- Many types of aquaculture facilities could be partially or wholly powered by marine energy. Most wave energy converters (WECs) prefer highly energetic sea states for energy production, which may not be suitable for aquaculture operations. However, some WEC designs are better suited to operate in less energetic conditions. WECs may provide shelter in their lee for aquaculture operations.

- The low surface expression of most WECs will increase survival at sea, provide low visual impacts, and be more readily integrated with aquaculture facilities.

Opportunity Summary

Aquaculture is the rearing of aquatic animals or the cultivation of aquatic plants for food. When used to produce fish, mussels, oysters, or similar organisms, it can produce high-quality protein with no need for land, fresh water, or fertilizer. In 2014, 73.8 million tons of fish were grown in global aquaculture operations, with an estimated first-sale value of $160.2 billion. China continues to be the major producer, providing slightly less than 62% of the world fish production in the past two decades. In 2014, the United States was the 17th top producer. Global aquaculture market growth is anticipated to accelerate through 2022 as a result of improvements in aquaculture systems, sustainable practices, and diversification of species (SeafoodSource 2018). Aquaculture operations have historically been limited to onshore or coastal sites, but in recent years groups are increasingly looking to offshore sites. These offshore sites will present unique challenges in terms of energy provisioning.

Aquaculture requires energy to power monitoring equipment, circulation pumps, feeding systems, and navigation lighting, as well as refrigerate the harvested product. These power needs are estimated to range between 4 and 715 megawatt-hours per year, depending on the size, location, and purpose of the operation (e.g., shellfish farm, fish farm). This power has historically been provided by diesel generation and only occasionally by renewables. By replacing fossil-fuel power generation with marine energy, the industry could reduce harm to air and water quality and lower operating expenditures.

Marine renewables are believed to be more suited to this task than other renewables because of excellent colocation characteristics, low visual profile, and reduced intermittency. U.S. waters include a large (almost 10 million km^2) Exclusive Economic Zone (EEZ) extending 200 nautical miles, a significant portion of which could be used for aquaculture development. The advantages of colocating the energy source with aquaculture operations could potentially favor a marine energy power supply for this growing industry.

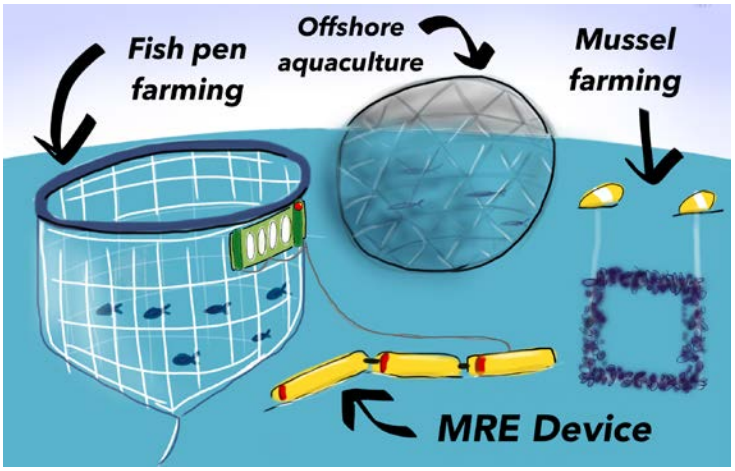

Figure 4.1. Marine renewable energy application overview for offshore marine aquaculture. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Application

Description of Application

Aquaculture is the cultivation of finfish, shellfish, crustaceans, and seaweeds on land or at sea, primarily for human consumption, with additional markets for animal feed and industrial chemicals (Figure 4.1). It is a nascent U.S. industry; however, offshore farms are developing worldwide to meet a global market projected to be more than $55 billion by 2020 (FAO 2016). Small aquaponics operations are under development nearshore on barges in the United States and in Europe (EzGro Garden 2016; Earth Institute 2011), and many are looking to expand to include additional hydroponic and aquaponic systems. Presently, marine aquaculture operational power needs include navigation lights, compressed air production, nutrient and waste disbursement, fish feeders, and crew support (e.g., lights, heat), all of which are currently met with diesel generators, battery storage, and solar panels.

There is an annual seafood trade gap of approximately $14 billion per year between the United States and its trading partners (National Oceanic and Atmospheric Administration [NOAA] 2015), which cannot be supplied solely by traditional fisheries. More than 90% of U.S. seafood is imported, presenting a unique opportunity for offshore and nearshore aquaculture, in addition to economic development and job creation. Offshore aquaculture is not well-developed in many parts of the world including the United States. Although many governments around the world (including the United States) support the development of offshore aquaculture, there are many economic and regulatory barriers that will have to be overcome to fully develop the sector (Knapp and Rubino 2016; Johnson et al. 2017).

Globally, approximately 3 billion people rely on seafood as a primary source of animal protein (NOAA 2015), yet most capture fisheries[9] worldwide are fully exploited or overexploited (Ye and Gutierrez 2017). In addition to seafood for human consumption, marine products are integral to meeting demands for animal fodder and many industrial chemicals. To ensure a sustainable seafood and marine products supply, growing organisms through aquaculture is needed to meet this demand. In 1974, aquaculture provided only 7% of fish for human consumption, increasing to 26% in 1994 and 39% in 2004 (FAO 2016). The United Nations FAO estimates that the world aquaculture production of fish and plants totaled $165.8 billion in 2014, increasing from approximately $42 billion in 1995 (Figure 4.2), resulting in a compound annual growth rate[10] of approximately 1.07%.

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[9] Capture fisheries refer to the harvesting of naturally occurring or wild fish populations in their native environment.

[10] The compound annual growth rate for the world aquaculture market between 1995 and 2014 was calculated by dividing the final market value ($165.8 billion) by the initial value ($42 billion) and raising the result to the power of 1 divided by the number of years (1/19 or 0.0526).

In addition to seafood for human consumption, aquaculture also supplies fishmeal, fish oil, and animal fodder; chemicals for the food processing, cosmetic, and industrial chemical industry (particularly from seaweeds); small fish and shellfish for aquaculture grow operations and bait; and specialty fish for the ornamentals trade (FAO 2016).

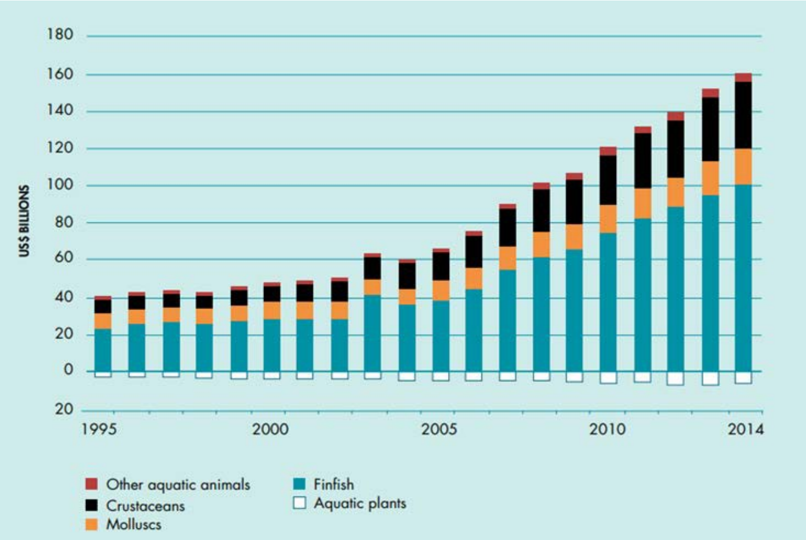


Figure 4.2. World aquaculture production volume and value of aquatic animals and plants (1995–2014).
Image from Food and Agriculture Organization of the United Nations (2016), reproduced with permission

Coastal Versus Offshore Aquaculture Operations

Aquaculture operations can occur in coastal or nearshore zones and deepwater or offshore areas. Coastal aquaculture is the most predominant form of aquaculture, where pens or fish cages are deployed along the coastline (often in a protected area). The majority of crustacean and mollusk farming occurs inshore, where racks are used for breeding (AquaBotix 2016). Other small coastal aquaculture operations are being developed on nearshore barges in the United States and Europe (EzGro Garden 2016; Earth Institute 2011). These barge operations are typically integrated with both hydrophonics and aquaphonics, often focusing on sustainable urban farming. Offshore aquaculture operations typically employ floating or submersible net pens or cages that are tethered to the seafloor and attached to buoys. Coastal and offshore pens are likely candidates for use of marine energy resources; moreover, offshore pens are becoming increasingly larger, requiring more power for lighting, bridge equipment, and feeding systems, for example (undercurrentnews 2018).

Finfish Aquaculture

Finfish, including anadromous fish, such as salmon, and marine fish, such as halibut, turbot, and black cod, are grown in net pens that are suspended off the seafloor or floating on the surface. These operations can be located in nearshore coastal waters or offshore (Figure 4.3 and Figure 4.4).

Figure 4.3. Open-ocean fish farming. *Photo courtesy of NOAA Fisheries*

Figure 4.4. Net pens for finfish rearing. *Photo courtesy of Creative Commons*

Figure 4.5. Shellfish farming. *Photo courtesy of Aquarium of the Pacific*

Shellfish Aquaculture

Most bivalve shellfish aquaculture in the United States is bottom-laid and does not require power except for maintenance or harvest vessels; some marginal growing waters could be made more productive with the addition of vertical advection of water from depth using low power pumps. However, certain shellfish species, notably mussels, require rafting on lines off the seabed, and increasingly, other shellfish are grown on lines or in suspended bags (Figure 4.5). Other shellfish species, such as shrimp, lobster, and other crustaceans, are generally grown in nearshore ponds that require relatively little power, which is generally supplied from a nearby electrical distribution network. Bivalve shellfish operations currently are mostly nearshore, but there is interest in growing shellfish further offshore, perhaps in conjunction with finfish or seaweed operations. This approach could increase power needs to levels similar to those for finfish.

Seaweed Aquaculture

Seaweeds for human and animal consumption are typically grown nearshore at locations around the world. Like bottom-laid shellfish aquaculture, these operations require little power except for harvesting, monitoring, and transporting. However, there is increasing interest in growing seaweeds offshore in conjunction with finfish or seaweed operations, which could require increased power for shellfish growing operations, similar to those of finfish. Aspects of this market beyond seaweed for food are discussed in more detail in the Marine Algae chapter of this report.

Multitrophic Aquaculture

Although only in the development phase, there is interest in growing multiple species of organisms together offshore, including finfish, shellfish, and seaweeds. These operations would include pens of different sizes and shapes, including growing surfaces on the seafloor. Using waste from one trophic level to feed the next, these growing operations can increase the product-yield-to-feed ratio dramatically. Power needs for multitrophic grow operations will resemble those for finfish aquaculture.

Power Requirements

Marine aquaculture operations require energy to power standard safety, navigation, and maintenance equipment; automatic fish feeders; refrigeration and ice production; marine sensors; recharging of AUVs; hotel loads for the crew living quarters (if the structures are manned); and transport vessels.

Large offshore and nearshore salmon operations may include living spaces for the onboard crew or they may be unmanned. Typical power needs for offshore finfish rearing are electricity for automatic fish feeders; living quarters and other amenities for crew; refrigeration of product; compressed air for aerating the pens and scaring away predators; and mechanical or electrical power for operating sensors for water quality monitoring and predator harassment. Other needs include powering maintenance/harvest and supply vessels operating between shore bases and the pens, as well as smaller vessels operating within a pen farm.

Measurements of actual power demands of aquaculture operations are scarce. Toner and Mathies (2002) provide energy load estimates for three land-based aquaculture case studies: a Pacific oyster farm, a rainbow trout farm, and a marine fish farm grown under recirculation. The researchers find that the power consumption for the Pacific oyster farm is similar to an average family home. For this operation, the purification system uses the most power (33.6 kilowatt-hours (kWh)/week), followed by the holding pond aerator (15.4 kWh/week). For the rainbow trout farm, the aeration system uses the most power (238 kWh/week), and for the marine recirculation farm, the recirculation system uses the most power (13,440 kWh/week).

Aquatera (2014) provides estimated requirements for energy and siting of modern aquaculture units. Although several of the estimates are based on freshwater operations, they can be used as a reference and general estimate. Aquatera (2014) also discusses the Greenius project, which aims to identify the power requirements of offshore aquaculture sites, identify the WEC sizes required from the WaveNET modular devices being developed by AlbaTERN to meet these requirements, and provide the necessary technical inputs to allow the physical and electrical incorporation of wave energy devices into an offshore aquaculture site, alongside other elements, such as power storage and backup power, to deal with wave resource variability. More detail can be found in Fiander et al. (2014).

Fish farms typically go through a 2- to 3-year energy demand cycle, which is closely correlated to the amount of biomass present and the stage in the production cycle that has been reached. These energy demand cycles are not necessarily in sync with marine energy resources (Aquatera 2014). The seasonal peaks of energy needs for fish farms may not correspond with the seasonal availability of marine energy resources. Siting of coupled systems must take into account the seasonal energy availability, and may be somewhat mitigated by coupling marine energy resources with energy storage systems.

Markets

Description of Markets

In 2014, 73.8 million tons of fish were grown in global aquaculture operations, with an estimated first-sale value of $160.2 billion, consisting of 49.8 million tons of finfish ($99.2 billion), 16.1 million tons of mollusks ($19 billion), 6.9 million tons of crustaceans ($36.2 billion), and 7.3 million tons of other aquatic animals including frogs ($3.7 billion) (FAO 2016) (Figure 4.6). World aquaculture production of fish accounted for 44.1% of total production in 2014, up from 31.1% in 2004 (Figure 4.6). Although Oceania's (geographic region comprising Melanesia, Micronesia, Polynesia, and Australasia) share of aquaculture production in total fish production has declined in the past 3 years, all continents have shown an increasing trend in the share of aquaculture production, particularly in relation to capture fisheries (Figure 4.7). Also highlighted in FAO (2016) are the groups of species produced from aquaculture in 2014, and include 362 species of finfishes (including hybrids), 104 mollusks, 62 crustaceans, 6 frogs and reptiles, 9 aquatic invertebrates, and 37 aquatic plants.

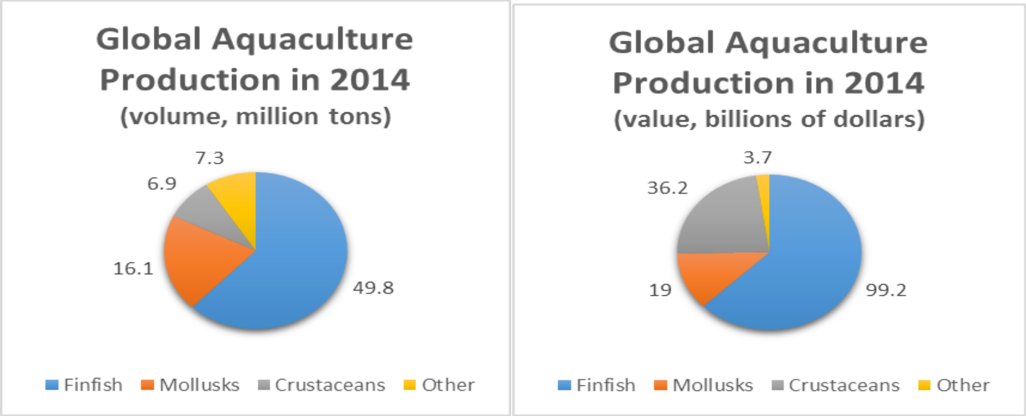


Figure 4.6. Global aquaculture production in 2014 in million tons (left) and billions of dollars (right). *Data from FAO (2016)*

Also highlighted in FAO (2016), China continues to be the major producer, providing slightly less than 62% of the world fish production in the past two decades. As the top aquaculture producer in 2014, China produced 58,798 thousand tons of total aquaculture. As the 17th top aquaculture producer in 2014, the United States produced 425.9 thousand tons of total aquaculture.

Marine aquaculture products are used as soil amendments as well as seafood, and this market is expected to grow (Markets and Markets 2018). The global soil treatment market was valued at $24 billion in 2015 and is expected to reach $39.5 billion by 2021, growing at a compound annual growth rate of 8% between 2016 and 2021 (GlobalNewswire 2016). This market consists of organic amendments, pH adjusters, and pest and weed controllers (Cision 2013). The Asia-Pacific region is estimated to be the fastest-growing region in the market in terms of revenue and volume. Markets in China, India, and Brazil are also expected to grow as a result of the rising demand for food caused by population growth (Cision 2013).

FAO (2016) estimates that the growing demand for fish and fishery products will mainly be met by growth in supply from aquaculture, which they estimate to reach 102 million tons by 2025. Asian countries are anticipated to remain the main producers in 2025, with significant increases expected in Latin America and Africa.

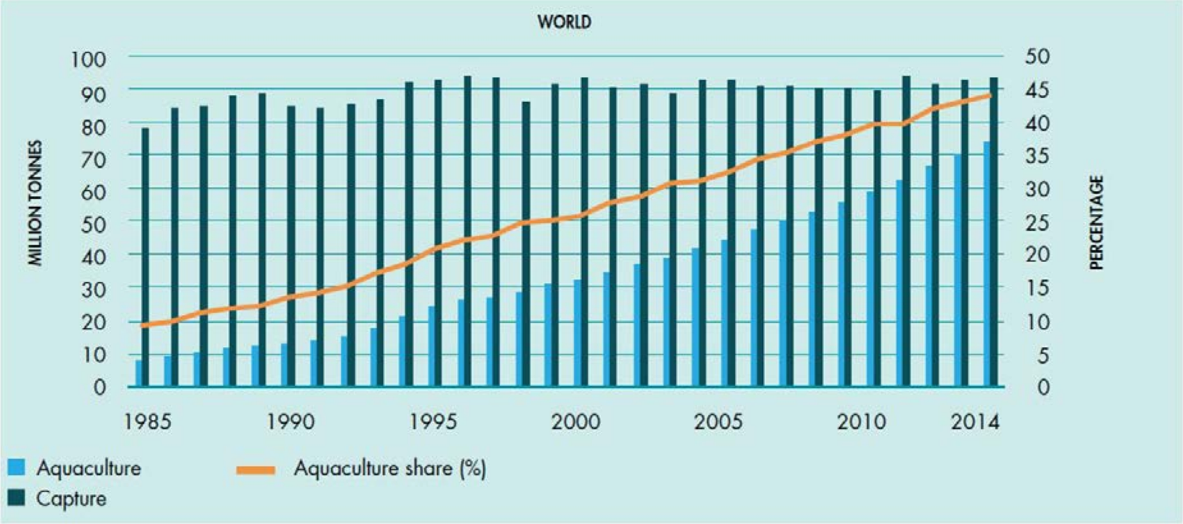


Figure 4.7. Global share of aquaculture in total production of aquatic animals. *Image from Food and Agriculture Organization of the United Nations (2016), reproduced with permission*

The United States has the world's largest EEZ, which extends 200 nautical miles offshore and encompasses diverse ecosystems and natural resources. The U.S. EEZ spans more than 13,000 miles of coastline and contains 3.4 million square nautical miles of ocean, which is larger than the combined land area of all 50 states (NOAA 2011). Still, the United States imports approximately 90% of all seafood consumed domestically by value (NOAA 2015), half of which is from aquaculture (NOAA 2017). The United States would still remain approximately 1 million metric tons short of fulfilling the current domestic demand for seafood if all U.S. fisheries exports were consumed domestically. This deficit results in a $14 billion seafood trade gap between the United States and trade partners. Encouragingly, U.S. marine aquaculture is estimated to increase approximately 19% by 2025, with an approximately 33% increase in exports and 30% increase in imports (FAO 2016).

Market Drivers for Aquaculture and Its Effects on Marine Energy Markets

The main drivers for aquaculture production are the increased global supply of fish for human consumption as a result of population growth, with estimates pointing toward further growth (FAO 2016). Aquaculture has been responsible for the growth in supply of fish for human consumption, as capture fishery production has been relatively static since the late 1980s (FAO 2016).

Three billion people rely on seafood as a primary source of protein and other nutrients essential for human health (Mozaffarian and Rimm 2006; NOAA 2015). The U.S. Department of Agriculture (USDA) and Food and Drug Administration has urged North Americans to increase their seafood consumption from the current level of one meal a week (USDA and Food and Drug Administration 2010), adding to the increased demand of fish for human consumption. Fresh seafood reaches only about 55% of American households, whereas one-third of U.S. households make up 80% of the sales (Luening 2017). With appropriate marketing and price points, there is significant room for growth and a further opportunity to augment seafood supplies with aquaculture products. Global fish consumption is expected to increase by 31 million tons to reach 178 million tons in 2025 as a result of rising incomes and urbanization, along with the expansion of fish production and improved distribution channels (FAO 2016). The main drivers affecting world fish prices are believed to be consumer income, population growth, costs of substitutes (e.g., beef, chicken, pork), and production costs (including fish feed and energy) (FAO 2016).

Currently, global aquaculture is dominated by low-trophic-level species groups (e.g., seaweeds, carp, and bivalves) that need relatively simple equipment and limited husbandry. With the growing demand for highertropic-level species (e.g., sea bass, salmonids, catfish, and shrimp), there will be a shift toward more intensive high-technology farming. This shift will drive increased energy needs for producers.

As a result of international requirements, pressure to reduce land footprints for food and other agricultural products, competition for scarce freshwater resources, and the expense of artificial fertilizers, the expanding aquaculture industry has good reason to seriously consider co-development with marine energy resources where possible.

Customers

Shore-based aquaculture operations may be a potential user of marine energy as a power source. For example, Fiander et al. (2014) discuss the potential for wave energy to pump water onshore at a low cost, enabling the development of profitable shore-based aquaculture methods. Scale-model and sea-based testing of this concept is currently underway at a shore-based aquaculture site in Lord’s Cove, Newfoundland (Fiander et al. 2014). Tidal energy could also be a potential energy source for shore-based and inland aquaculture operations.

Half of U.S. seafood exports by value originate in developing countries; these nations could benefit from the use of marine energy technologies to power aquaculture operations. Small- to medium-sized aquaculture enterprises tend to be highly entrepreneurial and innovative and assume significant financial and technical risks (Agence Francaise de Développement, European Commission, and Deutsche Gesellschaft für Internationale Zusammenarbeit 2017). Their acceptance of higher-risk opportunities may encourage them to embrace the use of marine energy sources for their operations (Table 4.1).

Table 4.1. Simple Classification of Aquaculture Types (Adapted from Agence Franca̧ise de Devéloppement, European Commission, and Deutsche Gesellschaft für Internationale Zusammenarbeit [2017])

	Commercial		Subsistence-Oriented	
	Industrial Aquaculture	Small-to-Medium Aquaculture	Small-Scale Commercial Aquaculture	Subsistence Aquaculture
Food and agriculture organization typology	Large-scale commercial	Small- to medium-sized enterprises	Small-scale aquaculture enterprises	
Production systems	Tanks (flow/ recirculated), cages, pond arrays	Tanks (flow), ponds, cages	Mainly ponds, lagoons, tanks, small cages/pens	Ponds (rain-filled)
Labor	Salaried employees	Mixed, presence of permanent employees	Mainly family members; activities are integrated into other small-holder farming activities	
Capital	Shared ownership	Family or family groups	Family ownership only	

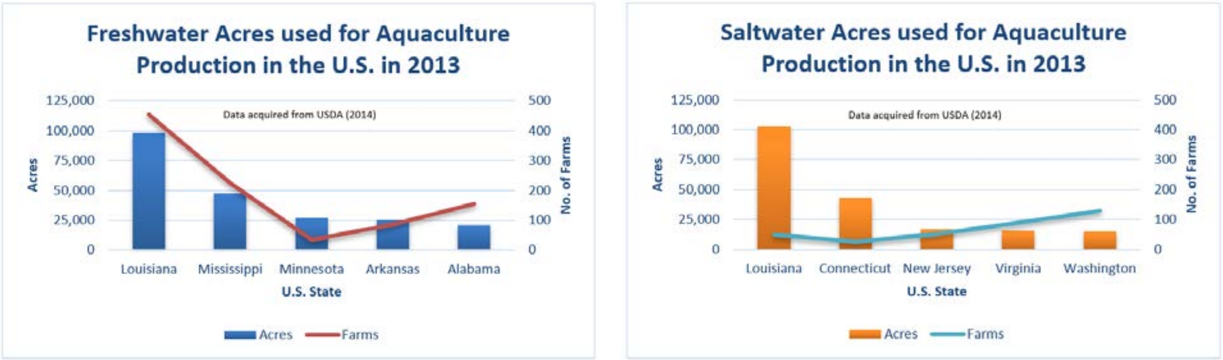
There are several U.S.-based aquaculture operations that may be interested in supplementing their power needs with marine energy. Catalina Sea Ranch is the first offshore aquaculture facility in the United States, with a 100-acre aquaculture facility on the periphery of the San Pedro Shelf. In 2017, Catalina Sea Ranch was awarded funding through the Advanced Research Projects Agency-Energy program to conduct macroalgae research. Manna Fish Farms is proposing a 1.5-square-mile facility off the coast of Long Island. The company is planning to build and operate a commercial fish farm and research integrated multitrophic aquaculture with kelp and sea scallops. InnovaSea Systems, Inc. develops aquaculture technologies, such as submersible pens. Customers of InnovaSea Systems, Inc. include Open Blue, Earth Ocean Farms, and Blue Ocean Mariculture.

Power Options

Aquaculture operations that require power have traditionally relied on diesel or kerosene generation from onboard generator sets with battery backup. Small shore-based aquaculture operations, particularly in developing countries, generally have little need for power, but in some cases, they may use battery power alone. More recently, some operations have used solar power. For example, low-cost solar thermal aerators are being developed to improve aquaculture in developing countries (Engineering for Change 2017). Additionally, the Lashto Fish Farm in Haiti uses 63 solar photovoltaic panels to generate approximately 15,000 watts to oxygenate fish tanks and charge and maintain battery systems (NRG 2018). In the United States, photovoltaic panels are being used to power a conventional floating upwelling system that is used to force-feed nutrient-rich water to infant shellfish (Energy Smarts 2013).

Geographic Relevance

In 2013, the USDA estimated that the United States operated 2,256 freshwater and 876 saltwater aquaculture farms, totaling 249,274 and 213,455 acres, respectively (USDA 2014). Of the freshwater farms, Louisiana topped the list, with 454 farms totaling 97,904 acres (Figure 4.8a). Of the saltwater farms, Louisiana also topped the list, with 103,159 acres across 48 farms (Figure 4.8b); however, Florida operated the most farms (169 farms only totaling 1,078 acres). Moreover, this vast amount of area shows substantial overlap with excellent marine energy resources. Typically, offshore net pens and other aquaculture enclosures are sited in the calmest waters that provide adequate flow to supply nutrients and clean water while removing waste. These calmer waters may not coincide with the best wave or current resources; however, there are likely to be many locations where adequate wave resources can generate the amount of energy needed by aquaculture operations, particularly offshore, where heavy-duty cages and enclosures can withstand greater wave activity. Tidal movement and energy generation is much more predictable than wave energy. Locations where aquaculture power needs and tidal energy generation potential might co-occur are limited, but some nearshore salmon farms (for example, in inlets in British Columbia, Canada) could benefit from replacing diesel power with tidal energy. The emerging industry is focused on large devices that operate optimally at tidal currents of 5–7 knots (1.5–3.5 meters per second); however, there are some devices designed to operate in lower current speeds, which could work well with aquaculture needs (Aquatera 2014). Most tidal devices have no surface expression or a low profile, allowing them to survive and compete with offshore wind in a similar manner to WECs. Tidal power, colocated with aquaculture installations, also has similar advantages to solar power for replacing diesel.



(a) (b)

Figure 4.8. Acres used for aquaculture production for (a) freshwater and (b) seawater. *Data acquired from USDA (2014)*

In the United States, 47% of aquaculture products are produced along the Pacific Coast, including Alaska and Hawaii; 15% in the Gulf of Mexico; and 38% on the Atlantic Coast (NOAA 2015). The U.S. Department of Energy (DOE) (2016) estimated that the potential wave power in U.S. waters is 2,640 terawatt-hours (TWh) per year (almost 300 gigawatts), with the largest wave power resources located in Alaska and along the West Coast. Although the magnitude of potential tidal power is smaller than wave power (approximately 3 gigawatts), it is concentrated and often in close proximity to major coastal load centers (DOE 2016).

Marine Energy Potential Value Proposition

Aquaculture can produce high-quality protein without the need for land, freshwater, or fertilizer. Marine aquaculture requires energy to power equipment like fish feeders and refrigerated product and transport workers, supplies, and product between the shore and farms. This power is generally provided by diesel generation and occasionally by renewables. Replacing fossil fuels with renewable marine energy could help reduce negative impacts to air and water quality.

It should be noted that highly energetic waters with high waves and winds may threaten the safety and survivability of offshore marine aquaculture operations and ability for species growth. Wave or current power most useful for aquaculture operations will be in lower resource areas and could provide power for aquaculture needs coupled with storage to smooth power delivery. There are, however, additional marine energy applications for supporting aquaculture in remote communities that are limited because of lack of energy infrastructure and/or high existing costs.

A strong driver for transitioning aquaculture from fossil-fuel sources to renewables will likely be due to concerns over local air and water quality from emissions, rather than the cost of energy. Price point will be a factor, but is believed to be less important than for many land-based markets. Although the price point among specific renewables will be a factor in the choice of power sources, factors that could favor marine energy include the low profile of wave or tidal energy converters for survivability at sea; the fact that marine energy operations are unaffected by waves and spray that would reduce efficiency for other generating sources (e.g., solar); and around-the-clock generation that will be particularly effective at high latitudes (compared to solar). Marine energy could be a preferred power source for low-profile aquaculture pens in high latitudes relative to solar, because space to accommodate photovoltaic panels may not be available because of the low profile of the pens.

Many types of aquaculture facilities could be partially or wholly powered by wave energy. Most WECs aimed at the commercial market require a mean annual significant wave height greater than 1 meter (Aquatera 2014). However, there are a number of WEC designs in development that could meet aquaculture needs, including several small devices that are designed to operate in less energetic conditions that may be suitable for fish farming (Aquatera 2014). WECs could be colocated with most aquaculture operations either offshore or nearshore, with devices built into breakwater structures for nearshore operations (Aquatera 2014) or moored offshore. Wave energy is a viable option for coastal-based aquaculture installations and for installations with high energy costs (Toner and Mathies 2002). Given the small power demands for most aquaculture installations, excess power could potentially be sent to the local grid.

There are a number of potential synergistic opportunities for colocation of aquaculture and wave energy devices (Aquatera 2014). Colocating aquaculture and WEC infrastructure could save on installation and capital costs for both systems. Large-scale wave farms may provide shelter in their lee, which would be beneficial for aquaculture operations (Aquatera 2014). The low profile of most WECs is valuable because of increased survival at sea, low visual impacts, and easier integration with aquaculture facilities, particularly compared with offshore wind. When competing with solar renewable power, wave energy can offer aquaculture power around the clock and in high latitudes in winter—both areas in which solar traditionally struggles.

Path Forward

The success of supplying marine energy to aquaculture is tied up in the expansion and commercial success of the aquaculture industry. Finfish aquaculture for human consumption is likely to continue to be the highest-value market. Although great strides have been made in technologies and research for marine fish husbandry, there are still investments needed to improve feeds and survival, particularly for juvenile fish. Other investments are needed to ensure that nonseafood products from marine species can be optimized, including research into high-value uses for fish meal and fish oil, as well as specific chemicals from seaweed, such as alginates, agars, and other organic long-chain compounds.

There have been very few attempts to link marine energy outputs to aquaculture operations. Close coordination with aquaculture researchers and operators will be needed for the marine energy industry to understand the needs of and opportunities for testing marine energy devices in conjunction with aquaculture pens or other facilities. In-water tests of net pens and marine energy devices will help to hone compatibilities between the systems and may help foster public acceptance of the new hybrid installations.

Potential Partners

Potential mission-driven partners for the marine energy industry include those from the government as well as private sector. Examples include NOAA Aquaculture and other U.S. Department of Commerce offices; U.S. Fish and Wildlife Service (Game) departments; and agriculture departments in coastal states (for example, Alaska Department of Fish and Game, California Department of Fish and Wildlife, Oregon Department of Agriculture, Washington Department of Agriculture, and Hawaii Division of Aquatic Resources, Animal Industry Division).

A number of marine energy and aquaculture companies have expressed interest in exploring linkages, whereas others are already engaged. Marine energy industry players already active in linking marine energy to aquaculture, or with strong interests in doing so, include international companies, particularly in Scandinavia and Scotland, such as Wave Dragon, Albatern, and Waves4Power. U.S. companies include Atmocean and Columbia Power Technologies.

There are many aquaculture companies worldwide that are interested in this space, particularly in China, South Korea, and the Philippines. U.S. companies with offshore aquaculture interests include Kampachi Farms, Catalina Sea Ranch, Manna Fish Farms, and Innovasea.

By developing and adapting marine energy devices to provide power for aquaculture operations, the marine energy industry could move the route to commercial-scale development along further, while gaining much-needed revenue. Although many of the devices that are most useful for aquaculture adaptation—particularly WECs—are likely to be small, there are some large aquaculture operations that could use the power from prototype-scale devices. The testing and experience at sea will assist with the pathway to larger devices.

Similar marine energy devices to those used for aquaculture will also be useful for powering the growth of very large macroalgae farms used to produce biofuels at sea and devices applicable for powering navigation markers and recharging underwater vehicles and autonomous ocean observation sites.

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