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STUDY

OFFSHORE AQUACULTURE A MARKET FOR OCEAN RENEWABLE ENERGY

OES OCEAN ENERGY SYSTEMS

This report was prepared by Pacific Northwest National Laboratory, the Blue Economy Cooperative Research Centre (BE CRC), and the Commonwealth Scientific and Industrial Research Organization (CSIRO) for the International Energy Agency Ocean Energy Systems (OES) Technology Collaboration Program.
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Acronyms

BE CRC	Blue Economy Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organization
ERSEO	Énergies Renouvelables au Service des Exploitations Ostréicoles
FLUPSY	Floating Upweller System
HOST	Hawaii Ocean Science and Technology
MARIBE	Marine Investment for the Blue Economy
MFF	multilevel floating farm
MUSES	Multi-Use in European Seas
OES	Ocean Energy Systems
ORE	ocean renewable energy
OTEC	ocean thermal energy conversion
PV	photovoltaic
TRL	technology readiness level
US DOE	US Department of Energy
WEC	wave energy converter
WPTO	Water Power Technologies Office

Units

GW	gigawatt(s)
GWh	gigawatt-hour(s)
HOG	head-on-gutted
km	kilometer(s)
kg	kilogram(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
m	meter(s)
MWh	megawatt-hour(s)
TW	terawatt(s)
TWh	terawatt-hour(s)
V	volt(s)
W	watt(s)

ABOUT OCEAN ENERGY SYSTEMS

OES is an intergovernmental collaboration whose purpose is to accelerate the viability, uptake, and acceptance of ocean energy systems in an environmentally responsible manner. OES advances research, development, and demonstration of technologies to harness energy from the ocean through international cooperation and information exchange. OES covers all forms of energy generation, in which seawater forms the motive of power, through its physical and chemical properties. OES does not currently cover offshore wind generation because seawater is not the motive of power. This effort documented in this report falls under OES's ongoing project to find alternative markets for ocean energy.

ABOUT THE US DEPARTMENT OF ENERGY WATER POWER TECHNOLOGIES OFFICE

The US DOE WPTO enables research, testing, development, and commercialization of emerging technologies to advance marine energy as well as next-generation hydropower and pumped storage systems for a flexible, reliable grid. To reduce marine energy costs and fully leverage hydropower's contributions to the grid, WPTO invests in early-stage research and technology design, validates performance and reliability for new technologies, develops and enables access to necessary testing infrastructure, and disseminates objective information and data for technology developers and decision-makers. WPTO is also increasing its focus on shorter-term water power technology application and adoption, particularly by considering the specific needs of diverse sectors and communities.

ABOUT THE BLUE ECONOMY COOPERATIVE RESEARCH CENTRE

Established in 2019, the BE CRC-Co Ltd (ABN 64 634 684 549) is an independent not-for-profit company limited by guarantee and a Cooperative Research Centre under the Australian Government's CRC Program. With a 10-year life and a budget of more than $329 million, the BE CRC brings together 40 industry, government, and research partners from 10 countries with expertise in aquaculture, marine renewable energy, maritime engineering, environmental assessments, and policy and regulation. Through targeted industry-focused research and training, the BE CRC paves the way for innovative, commercially viable, and sustainable offshore developments and new capabilities.

The BE CRC's research is focused on partner needs, is environmentally and socially responsible, and will have a demonstrable commercial impact. Their research portfolio is structured into five integrated programs: Offshore Engineering and Technology, Seafood and Marine Products, Offshore Renewable Energy Systems, Environment and Ecosystems, and Sustainable Offshore Developments. Combined, these programs will deliver the knowledge needed to enable current and new industries to increase seafood and renewable energy production. This includes developing technologies and production systems that can withstand both regular and extreme weather events while being safely and economically managed. It will deliver knowledge to underpin new planning, regulatory, and monitoring systems that encourage and support sustainable capital-intensive operations while giving the community confidence that the operations will be environmentally sustainable and socially responsible.

The BE CRC is established and supported under the Australian Government's CRC Program, grant number CRC-20180101. The CRC Program supports industry-led collaborations between industry, researchers, and the community. Further information about the CRC Program is available at www.business.gov.au.

EXECUTIVE SUMMARY

As ocean-based development continues to increase, sustainable growth and solutions derived from marine activities offer opportunities to mitigate climate change and other sustainability challenges, such as resource exploitation and pollution. The possibility to co-locate marine infrastructure, or bring together compatible activities, will provide solutions for efficient and sustainable use of the ocean.

Ocean renewable energy (ORE) and offshore aquaculture are two industries that are likely compatible for co-location; ORE has the potential to provide power for offshore aquaculture and can decrease the environmental impact of operations by providing power at sea and replacing the reliance on diesel. This report defines co-location as the sharing of marine space between aquaculture and ORE as well as ORE providing power to aquaculture operations.

All forms of energy that can be derived directly from the seas and oceans are collectively known as ORE. Energy resources from the ocean are large, geographically diverse, and can be a sustainable alternative to providing power for offshore aquaculture. Each technology used to extract energy from waves, tides, ocean currents, or thermal and salinity gradients presents both advantages and challenges for aquaculture. Wave energy devices can be used for onshore, nearshore, or offshore aquaculture. They are particularly well suited for offshore aquaculture, though co-located wave and aquaculture projects will need to be in areas that avoid waves that are too large for the aquaculture system or too small for the wave energy device to be effective. Tidal energy devices may be more suitable for nearshore aquaculture operations, though the flow speed of tidal currents in energetic tidal channels could be a challenge for aquaculture operations. Both wave and tidal device technologies are more advanced than the other ORE technologies. Ocean current energy is generally located in offshore areas that feature high current velocities. For this reason, ocean current technology may not be suitable for offshore aquaculture because these locations present challenges for underwater operations such as net repairs and diving. Ocean thermal energy conversion (OTEC) has the potential to be used for onshore, nearshore, and offshore aquaculture in tropical and subtropical regions. OTEC can provide cold, nutrient-rich water with fewer pathogens and bacteria and can produce desalinated water for use in aquaculture production. Salinity gradient technologies are usually located nearshore and provide brackish water that can be supplied to aquaculture operations; however, these technologies are less developed than other forms of ORE. Solar photovoltaic (PV) and offshore wind are also assessed in this report as alternative renewable energy sources for powering aquaculture operations.

Worldwide, the aquaculture industry continues to increase. This expansion, coupled with increased competition for space among various marine uses, has led to an interest in shifting operations farther offshore. By moving away from coastal areas, aquaculture offers an important market opportunity for ORE. To develop appropriate ORE power systems for aquaculture and advance the co-location of the ORE and offshore aquaculture industries, understanding the energy demands and energy-intensive resource requirements for different aquaculture operations is crucial. Currently, data from the aquaculture industry on specific energy needs is limited, particularly for offshore aquaculture.

This report presents the available energy information for several operations within the global aquaculture sector, including nearshore and offshore Atlantic salmon, nearshore Asian seabass or barramundi, and nearshore oyster and mussel operations. As this report demonstrates, energy demands vary greatly by operation and species. Additionally, each source of energy information reports energy requirements differently, making it difficult to compare systems. The available energy information from marine-based aquaculture operations described in this report helps to provide a picture of the energy requirements worldwide.

Aquaculture projects that are being developed have begun to include renewable energy technologies (ORE as well as solar PV and offshore wind energy) in their designs and planning. The synergistic opportunities for co-located aquaculture and renewable energy can provide a multifunctional use of space and resources, creating opportunities to automate operations for safety and sustainability. Several projects, both past and present, are researching or have successfully implemented renewable energy to meet the identified energy demands of a variety of aquaculture operations. This report highlights 12 case studies, exploring projects that have used ORE, solar PV, offshore wind technologies, or hybrid solutions to meet energy demands of aquaculture. These case studies include all marine-based aquaculture types (finfish, shellfish, crustacean, and seaweed; nearshore and offshore) and a diverse range of renewable energy technologies. The key lessons learned from these projects are related to the lack of funding and the high cost of renewable energy technologies, long and costly consenting and regulatory processes, and uncertainty among stakeholders and regulators about the effects of a device on aquaculture operations.

Both offshore aquaculture and ORE are relatively new industries, but the opportunities and challenges related to co-locating these marine uses can be identified from existing and planned projects. The opportunities and challenges for co-locating ORE and offshore aquaculture have been categorized under three themes: technical and operational processes, regulatory processes (including environmental and social aspects), and economic impact. Examples of opportunities under the theme of social acceptance are the sustainable and efficient use of marine space and the development of multi-use platforms. Examples of challenges under the theme of technical and operational processes are limited energy storage and the low levels of ORE device commercialization.

To overcome the challenges and capitalize on the opportunities identified in this report, recommendations are provided to expand the potential for co-location and further understanding of powering offshore aquaculture with ORE. The recommendations are classified using the same themes identified from the opportunities and challenges. These recommendations include increasing the accessibility of information about energy demands for all types of aquaculture (nearshore and offshore; finfish, shellfish, seaweed, etc.; at varied geographic locations), creating partnerships between ORE and aquaculture industries to generate pilot project opportunities, conducting research on the environmental and social effects of co-location, identifying countries with planning and licensing frameworks that may foster co-location, and encouraging governments to provide funding for research efforts and industry development.

Overall, this report provides a comprehensive look into offshore aquaculture as a market for ORE by identifying ORE technologies to be used, aquaculture energy demands, case studies and lessons learned, opportunities and challenges, and finally recommendations to advance the potential for co-location.

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1.

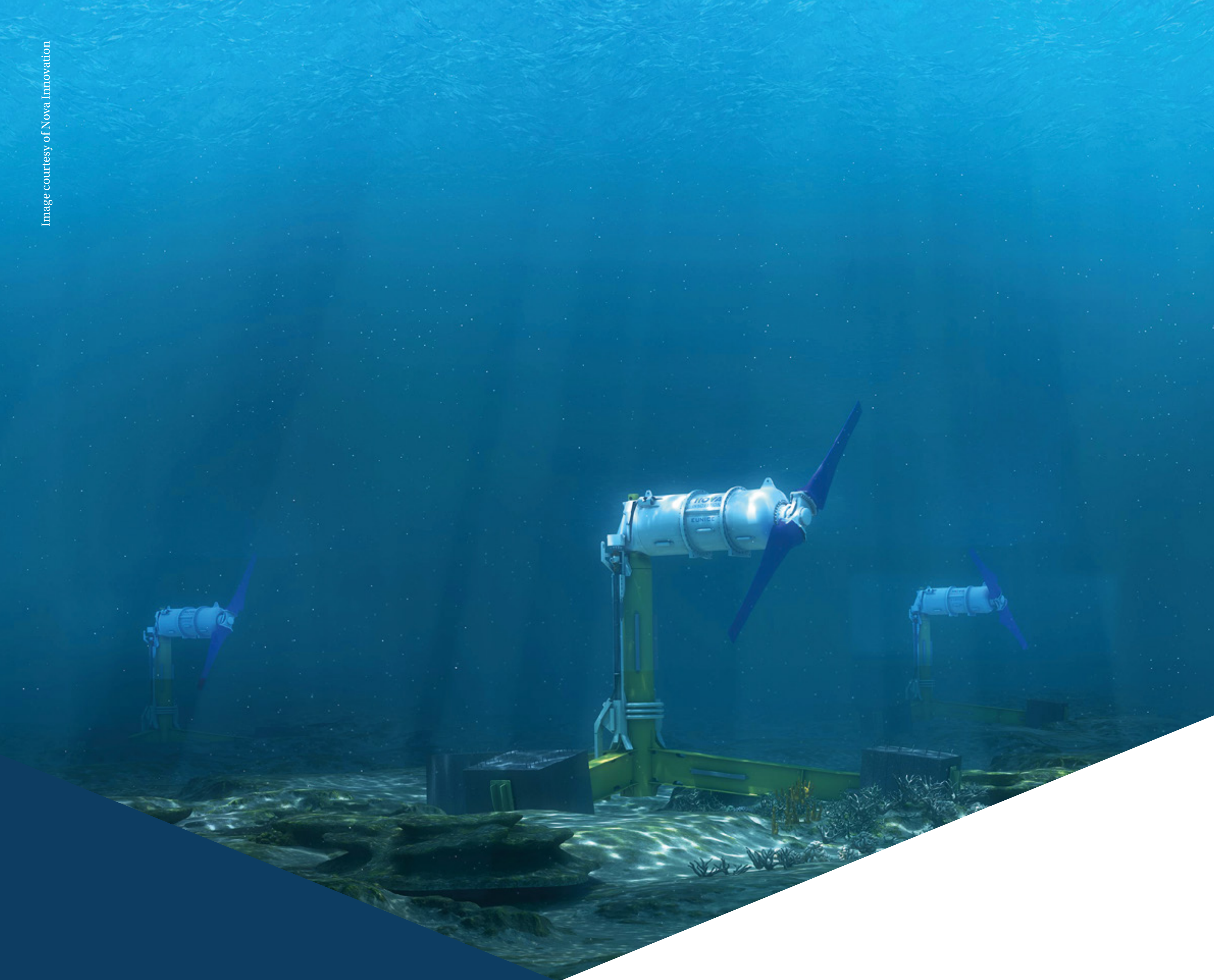
INTRODUCTION

Strategic planning for the growing ocean and coastal industries, as part of the blue economy, offers solutions to combat climate change and other sustainability challenges, from resource exploitation to pollution (Bax et al. 2021). Globally, the blue economy is worth an estimated US$1.5 trillion and continues to flourish rapidly (OECD 2016). As coastal and ocean-based development grows, the conflict between uses is likely to intensify, especially as new industries, such as ocean renewable energy (ORE) or aquaculture, increasingly compete for space. Managing the spatial use of marine resources comprehensively, via marine spatial planning processes, has typically involved distributed zones for different sectors, excluding activities to enable another (Smith et al. 2012; Jones et al. 2016). An alternative for sustainable and efficient use of the marine domain is co-locating compatible activities to share space. Some examples of co-location include marine-based tourism and offshore wind farms, offshore wind and ORE, and ORE and aquaculture (Schultz-Zehden et al. 2018; van den Burg et al. 2019). In this report, co-location is defined as marine uses developed within the same space and timescales and it specifically focuses on both integrating and powering aquaculture with ORE.

Globally, there is great potential to harvest energy from the ocean (Melikoglu 2018). ORE provides low-carbon emission renewable energy, and although it is a developing industry, it offers a viable alternative in the energy transition away from traditional fossil fuels. ORE has primarily been thought of as exporting power to the grid, but it can also provide power at sea or for off-grid coastal communities, especially for uses that are currently powered by diesel or other nonrenewable sources and are facing limitations (e.g., distance to shore) or high costs of traditional energy sources (LiVecchi et al. 2019). A preliminary assessment of the opportunities for ORE to power existing or new ocean-based activities identified offshore aquaculture as a promising market (LiVecchi et al. 2019). This assessment included detailing energy-specific uses and demands in offshore aquaculture and highlighted the relative scarcity of data in the available literature and the need for a more focused effort to quantify the energy needs for aquaculture and available ORE resources.

Marine-based aquaculture provides a low-impact protein source and support to coastal communities through job creation, economic development, and food security (Olaganathan and Kar Mun 2017; Lester et al. 2018a). As the aquaculture industry continues to grow globally due to an increasing need for global food access and security (FAO 2020), it is moving farther offshore to accommodate larger operations, avoid competing uses for space, and reduce environmental effects often seen with nearshore operations (Di Trapani et al. 2014; Soto and Wurmann 2019; FAO 2020). Typically powered by diesel generation, the aquaculture industry is beginning to utilize power from renewable sources, mainly solar installations with onsite battery storage (Vo et al. 2021; Chang et al. 2022). ORE represents another opportunity for alternative energy sources to power aquaculture operations, especially in new, more exposed offshore environments.

This International Energy Agency Ocean Energy Systems (OES) report aims to assess the potential of offshore aquaculture as a market for ORE. Because offshore aquaculture is still emerging, little information is available about this sector of the aquaculture industry. Therefore, this report also includes information and data from studies and projects related to onshore and nearshore aquaculture. **Chapter 2** introduces the different types of ORE by resource and technical attributes for co-location with aquaculture and details advantages and challenges for each technology to power aquaculture. Chapter 2 also includes information about other renewable sources—offshore wind and solar energy—that are either being used or considered for aquaculture. **Chapter 3** provides an overview of the status of the aquaculture industry in a few key countries—mainly OES member nations, large aquaculture-producing nations, or those who are interested in offshore aquaculture—and includes examples of energy requirements for different aquaculture operations around the world. **Chapter 4** highlights case studies from projects that are conducting research on or have successfully implemented renewable energy, both ORE and other renewable sources, to meet the energy demands of aquaculture operations. These case studies provide examples of past and current efforts and lessons learned. **Chapter 5** discusses both general and country-specific opportunities and challenges for co-locating offshore aquaculture with ORE. **Chapter 6** offers recommendations for further research needs and for identifying potential pathways for the expansion of co-location opportunities based on the findings of this report.



2. OVERVIEW OF RENEWABLE ENERGY TECHNOLOGIES AND ATTRIBUTES FOR CO-LOCATION WITH AQUACULTURE

All forms of energy that can be derived directly from the seas and oceans are collectively known as ORE, which includes waves, tides, thermal and salinity gradients, and ocean currents. Each resource is extracted differently, making ORE technologies suitable for a large range of locations and applications. This chapter focuses primarily on ORE and its application to aquaculture installations (both nearshore and offshore) but also explores the potential of other renewable energy sources, such as offshore wind and solar photovoltaic (PV) energy. This chapter outlines the basic function of each renewable energy technology and describes the technical attributes that offer advantages or potential challenges for application to the aquaculture sector.

2.1 Description of Renewable Energy Technologies

Wave energy is generated by absorbing the energy from ocean waves and converting it into electricity. Wave energy is a relatively continuous source of energy depending on the location (Pelc and Fujita 2002). The total wave resource is estimated to be 2,000 GW globally, equivalent to the world's electricity consumption (Barstow et al. 2008). Technologies used to extract wave energy are known as wave energy converters (WECs). WECs extract energy from waves according to their height, length, or direction of propagation. There are several categories of WECs (e.g., point absorber, oscillating water column, etc.) and many different technology designs, purposely built to suit a specific method of energy extraction and for specific applications, such as defined water depths or locations (shore-based, nearshore, or offshore). Wave energy devices can be placed on the seabed or can float within the water column or on the surface, and can also be attached to structures, such as piers. As the aquaculture industry continues to move offshore, aquaculture operations will become exposed to more energetic wave conditions. Harvesting wave energy via WECs can exploit these environmental conditions to provide power to the required aquaculture systems (OES 2021a). Wave energy devices could provide shelter from waves for aquaculture operations (Silva et al. 2018), but more research will be needed to fully understand this opportunity. Several commercial WECs have been developed to power specific aquaculture installations (see case studies in Chapter 4).

Tidal energy is a predictable source of ORE (Pelc and Fujita 2002) with the total tidal resource estimated to be around 120 GW globally (Offshore Energy 2015). There are two main categories of tidal technologies: tidal stream, or current, and tidal impoundment. Tidal stream devices use the rotation of turbines from tidal currents to capture and convert the kinetic energy of the tides to electricity, while tidal impoundment technologies (barrage, lagoon) use retaining walls with low-head turbines to create a reservoir that captures the potential energy in the height difference of rising and falling tides (Jo and Hwang 2020; Tethys 2022a). Both tidal stream and impoundment technologies can provide continuous and predictable power from tidal energy, but tidal impoundment technologies have a bigger footprint and have a larger impact on the surrounding environment (e.g., reduced habitat, low water quality) (Jo and Hwang 2020). Currently, tidal stream devices under development span a range of technologies, including horizontal and vertical axis turbines and tidal kites. Tidal stream devices can be stationed on the seafloor, floating with moorings attached on the seafloor, or attached to a floating platform. Because tidal energy devices are typically sited closer to shore and in restricted channels, these devices could be placed in energetic tidal streams adjacent to nearshore aquaculture operations to meet associated power requirements. The use of tidal energy may be more relevant for nearshore operations and particularly for bivalves and seaweed aquaculture (see case studies in Chapter 4). Tidal energy may not be suitable for finfish aquaculture because fast-moving tides are challenging for fish feeding. Both wave and tidal energy devices are in more mature stages of development compared to other forms of ORE (Pelc and Fujita 2002), making them more likely to provide solutions for powering aquaculture.

Ocean currents (wind- and density-driven) are predictable and constant and carry large amounts of energy. Worldwide, the total ocean current energy is estimated to be 5,000 GW (Burman and Walker 2009). The turbines extracting ocean current energy have a design similar to tidal stream turbines but are usually larger. These devices can be suspended from moored surface platforms or attached to buoyant structures tethered to the seabed. Because high ocean current velocities can affect underwater operations, such as diving to inspect net pens and fish feeding, ocean current energy may not be suitable for offshore aquaculture though it may depend on a species feeding behavior. Because of the early development stage of ocean current energy devices, their uses for aquaculture may be limited.

Ocean thermal energy conversion (OTEC) is a process that uses the temperature difference (20ºC minimum) between warm waters from the ocean surface and cooler waters from the deep ocean to capture energy through thermal heat engines. Such temperature differences can be found in tropical and subtropical oceans. There are large areas of the ocean with temperature differences suitable for OTEC, including about 60 million km^2 deemed to be most suitable, with an estimated power of 0.2 MW per km^2 (Golmen et al. 2005). The globally available resource for OTEC could be up to 30,000 GW (Rajagopalan and Nihous 2013). Many different OTEC archetypes have been assessed—from floating offshore platforms to onshore systems with pipelines to transport the water to and from the ocean (Tethys 2022b). The process of deriving energy from an OTEC plant brings deep seawater to the surface and could provide cold, nutrient-rich water with fewer pathogens and bacteria for use in aquaculture production (Daniel 1985; OES 2021b). OTEC can also provide desalinated water, which is suitable for aquaculture operations that require freshwater (Herrera et al. 2021). OTEC has been used to power aquaculture installations (see case studies in Chapter 4).

Salinity gradient technologies use the chemical pressure differential from the ionic concentrations of fluids (i.e., difference in the salt concentrations of fresh and saltwater, such as river and seawater) to generate power (IRENA 2014; Tethys 2022c). The main applications for salinity gradient technologies are plants in estuaries and hybrid energy generation processes in high salinity waste streams (IRENA 2014). Reverse electrodialysis and pressure-retarded osmosis are the two main technology types for salinity gradients. Reverse electrodialysis generates electricity from the controlled mixing of two fluids with different salinities. Pressure-retarded osmosis generates electricity by converting the osmotic pressure between fluids/solutions with different salt concentrations to hydraulic pressure, which can then be converted to mechanical or electrical energy via a turbine or generator (or a combination of both). Besides generating electricity, these processes also create brackish water that can be supplied to aquaculture operations. To date, salinity gradient technologies have mostly been used for energy recovery in desalination systems (OES 2021c).

While the purpose of this report is to highlight the market for ORE to power aquaculture installations, it is important to also consider other renewable energy resources and their potential to meet these energy demands. **Solar energy** is the most abundant renewable energy source and is harnessed through PV systems (Kannan and Vakeesan 2016). Solar PV systems are electronic devices that convert sunlight into electricity (Oliveira-Pinto and Stokkermans 2020). In recent years, the floating solar PV industry has seen a rise in installations. As of August 2020, the total installed capacity of floating solar PV worldwide reached 2.6 GW, with more than 60 countries exploring the possibility of utility-scale projects (Gray 2020). These installations are primarily located within man-made, freshwater systems, but marine deployed systems also are emerging (Hooper et al. 2021). Although the use of non-floating solar PV is more common, floating solar PV has been used to power aquaculture installations (see case studies in Chapter 4).

Offshore wind energy consists of harnessing kinetic energy from the wind to generate power in bodies of water. Offshore wind turbines are similar to land-based wind turbines, but they are larger to harness the stronger and more consistent winds offshore. Turbines can be fixed to the seafloor (bottom-mounted) or floating. As of 2020, the total offshore wind power capacity was 33.3 GW worldwide (GWEC 2021). Currently, the vast majority of offshore wind energy is fixed, but floating operations are emerging. To date, efforts to pair offshore wind with aquaculture have mainly focused on the shared use of space and have only occasionally focused on the ability to provide power for aquaculture (CORDIS 2019; MUSES 2022). Because large vessels are typically excluded from offshore wind sites, co-locating aquaculture and offshore wind could reduce the risks of vessels colliding with aquaculture farms (MARIBE 2018). Fixed platform offshore wind farm facilities could be used as feed barges for aquaculture. For offshore sites, the use of offshore wind has challenges similar to those of ORE technologies, in that floating technologies have limited development or unknown cumulative effects. However, smaller-scale micro-wind turbines could offer additional opportunities to meet offshore energy demands associated with smaller-scale aquaculture electricity requirements (e.g., monitoring systems) (SARF 2014).

2.2 Technology Readiness Levels of ORE

Technology readiness levels (TRLs) are globally adopted metrics used for tracking the progress of ORE technologies, and aiding in their systematic development for in situ use. TRLs are used throughout the development chain, from early, primarily research levels (TRL1–3) to full-scale system demonstrations (TRL7–9). Differences in TRLs are related to technology-specific challenges such as reliability, survivability, maintainability, and affordability. While higher TRLs are related to technologies that have more cumulative experience (e.g., in terms of total installed power) and a more developed supply chain, lower TRLs show the need to overcome sectorial challenges, mainly by focused research and development, innovation, and development of the supply chain.

As outlined in this chapter, there are numerous forms of ORE technologies, each at a different stage of technology readiness. Figure 1 demonstrates the TRL for each ORE technology, considering its relative progress throughout development and operation. Salinity gradient and ocean current technologies have the lowest TRL (between 4 and 5), and tidal technologies have the highest TRL (between 7 and 9).

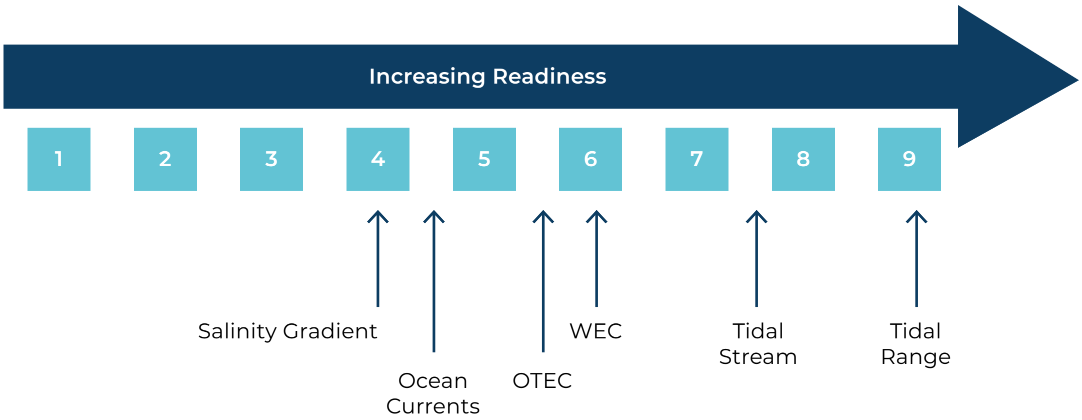


Figure 1. Technology readiness level of ocean renewable energy technologies (Ji et al. 2016). OTEC = ocean thermal energy conversion; WEC = wave energy converter.

2.3 Advantages and Challenges of Using Renewable Energy Technologies to Power Aquaculture

Table 1 outlines the potential advantages and challenges of using each ORE technology, as well as solar PV and offshore wind, and its application to aquaculture installations. There are several common advantages for using renewable sources of energy for aquaculture including:

- Reducing or removing requirements for fuel;
- Contributing to cost savings due to energy being supplied by onsite resources;
- Avoiding potential for fuel spills and associated environmental effects;
- Minimizing noise by running generators for fewer hours;
- Providing opportunities to integrate with other offshore renewable energy systems, including hydrogen, solar, and batteries;
- Scaling technologies to be suitable for large and small aquaculture installations (except for tidal impoundment); and
- Offering a diversity of technologies that allows for various applications and location-specific uses (except for OTEC and tidal impoundment).

While the various ORE technologies present specific advantages and challenges for aquaculture applications (Table 1), the inclusion of such technologies is not a straightforward process. Integrating ORE technologies with aquaculture systems requires several pre-development activities including, but not limited to, techno-economic analysis, engineering design, and optimization (e.g., sizing) to ensure a good fit with the aquaculture energy system and the application/user needs. Existing aquaculture operations may have limited options for co-location due to certain practical constraints such as the scale of operation or the location of the aquaculture site. However, aquaculture sites that have the necessary approvals to use the licensed area may present an easier opportunity for deploying an ORE device. Nevertheless, the application of ORE technologies is a consideration that many aquaculture developers are exploring, especially as they move toward sustainability, both for operations and for marketed products. Aquaculture projects that are being developed have begun to include renewable energy technologies in their designs and planning, which may add some layer of complexity to the licensing process. Some of these existing and new co-located projects are presented as case studies in Chapter 4.

Table 1. Potential advantages and challenges of ocean renewable energy (wave, tidal, ocean current, thermal gradient, salinity gradient), solar photovoltaic, and offshore wind technologies for powering aquaculture operations.

Renewable energy technology	Potential advantages for aquaculture	Potential challenges for aquaculture
Wave Energy Converters	• Suitable for onshore, nearshore, and offshore aquaculture sites.	• High cost of technology installation. • Resource variability and intermittency. • High-energy sites may not be ideal/suitable for certain types of aquaculture operations.
Tidal Stream	• Resource predictability and power scheduling with a high degree of accuracy. • Resources available year-round. • Suitable for onshore and nearshore aquaculture sites. • Natural water flow at sites may facilitate flushing of organic waste from aquaculture. • Baseload power is possible.	• High cost of technology installation. • High-energy sites may not be ideal/suitable for certain types of aquaculture operations.
Tidal Impoundment	• Resource predictability and power scheduling with a high degree of accuracy. • Resources available year-round. • Suitable for onshore and nearshore aquaculture sites. • May readily provide a brackish water environment useful for aquaculture. • Baseload power is possible.	• High cost of technology installation. • Environmental effects are likely with tidal impoundment technologies.

Renewable energy technology	Potential advantages for aquaculture	Potential challenges for aquaculture
Ocean Current	• Resource predictability and power scheduling with a high degree of accuracy. • Resources available year-round. • Suitable for offshore aquaculture sites. • Natural water flow at sites may facilitate flushing of organic waste from aquaculture. • Baseload power is possible.	• High cost of technology installation. • Remoteness of some offshore sites may increase operating expenses. • High-energy sites may not be ideal/ suitable for certain types of aquaculture operations.
Ocean Thermal Energy Conversion	• Resource predictability and power scheduling with a high degree of accuracy. • Resources available year-round. • Suitable for onshore, nearshore, and offshore aquaculture sites. • Increased access to cold, nutrient-rich waters. • Access to desalinated water. • Baseload power is possible. • Infrastructure could be used to implement feeding systems and other components of aquaculture installations that require platforms.	• High cost of technology installation. • Only suitable in tropical and subtropical regions.
Salinity Gradient	• Resource predictability and power scheduling with a high degree of accuracy. • Suitable for nearshore areas. • Can provide access to freshwater, saltwater, and brackish water. • Baseload power is possible.	• High cost of technology installation. • Technology still in early stages of development.
Solar Photovoltaic	• Solar technology is more advanced. • Infrastructure could be used to implement feeding systems and other components of aquaculture installations that require platforms.	• Resource variability and intermittency. • May need to mitigate effects of heat/ radiation on the sea surface. • Requires large areas of the ocean to deploy.
Offshore Wind	• Fixed offshore wind technologies are more advanced. • Infrastructure could be used to implement feeding systems and other components of aquaculture installations that require platforms. • Can reduce risk of vessel collision.	• Resource variability and intermittency. • High-energy sites may not be ideal/ suitable for certain types of aquaculture operations. • Wind farm setup may constrain certain operations (i.e., limited vessel movements around aquaculture operations).

3.
OVERVIEW OF AQUACULTURE AND ENERGY NEEDS

Broadly defined, aquaculture can include the cultivation of seaweed (e.g., Eucheuma, dulse, Japanese kelp, Wakame, etc.), crustaceans (e.g., crab, lobster, shrimp, etc.), shellfish (e.g., oysters, mussels, scallops, abalone, etc.), and finfish (e.g., salmon, tilapia, seabass, etc.) for human consumption, protein for aquaculture or agriculture feed, ornamental trade, cosmetics, or other purposes such as biofuels.

3.1 Aquaculture Overview

Aquaculture (both land-based and marine-based operations) on a global scale has continued to increase over time. As of 2018, aquaculture accounted for 46% of world fish production, producing 82.1 million tonnes of live weight (FAO 2020). Globally, aquaculture is most prevalent in northern temperate areas, followed by the equator, arctic, and southern temperate areas (Kapetsky et al. 2013). The amount produced varies by region; aquaculture accounted for 42% (30 million tonnes) of total fish production (both aquaculture and capture fisheries) in Asia in 2018 (excluding China, which is 76.5% or 47 million tonnes); 16 – 18% (3-4 million tonnes) in Africa, North and South America, and Europe; and 12.7% (2 million tonnes) in Oceania (FAO 2020). Marine aquaculture (operations in coastal/nearshore or offshore areas) makes up a smaller portion of total aquaculture production, because the majority of current operations occur inland (FAO 2020). In 2018, marine aquaculture produced approximately 30 million tonnes worldwide, which was dominated by shelled mollusks contributing 18 million tonnes, followed by 7 million tonnes of finfish and 6 million tonnes of crustaceans (FAO 2020). These numbers did not include seaweed and aquatic plant production, which alone accounted for around 30 million tonnes produced, though this included both land-based and marine-based production (FAO 2020).

Offshore aquaculture is a novel and evolving aspect of the aquaculture sector and there have only been a small number of operations to date (California Environmental Associates 2018). Note that there is no standard definition of "offshore" aquaculture (Froehlich et al. 2017), although a few sources define offshore by depth or distance from shore or generally by an environment exposed to ocean waves (Ryan 2004; Lester et al. 2018b; Morro et al. 2021). Some examples of offshore aquaculture include Ocean Farm 1, Deep Blue 1, and Aquatraz. Ocean Farm 1, the first offshore fish farm, was designed in China and deployed 30 km off the coast of Norway in 2017 with a capacity of about 1 million salmon (about 6,000 tonnes) (Jin et al. 2021; SalMar 2021). Rizhao Wangzefeng Fishery and China Ocean University developed the Deep Blue 1 system that was launched in 2018 in China 48 km off the coast in Shandong Province (Evans 2021). Deep Blue 1 can hold 200,000 salmon (around 1,000 tonnes) with further iterations (Deep Blue 2) able to hold up to 420,000 salmon (Evans 2021). Midt-Norsk Havbruk and Seafarming Systems have developed the Aquatraz salmon farming system that has been tested in Norway since 2018 and to date has four iterations (G1, G2, G3, and G4) of the cage system (Aquatraz 2022). Other offshore developments are being considered, including many new designs and ideas for offshore farming, such as Ocean Arks Tech's offshore aquaculture vessel in Chile that could have a capacity to produce up to 3,900 tonnes of salmon, or other commercial finfish species (Ocean Arks Tech 2017).

As the aquaculture industry continues to expand worldwide and seeks to shift marine operations farther offshore, there is great potential for co-locating aquaculture with ORE (LiVecchi et al. 2019). Table 2 summarizes the current state of aquaculture by country, focusing mainly on OES countries; plans for offshore expansion of the aquaculture sector; and suitability of ORE for current and future aquaculture operations.

Table 2. Overview of aquaculture by country, including the existence of current offshore aquaculture operations, expansion plans to move aquaculture offshore, and suitability for ocean renewable energy. Data were collected from aquaculture experts in each country and supplemented with provided reports and additional information. Blank cells in the last three columns mean no information was provided by the aquaculture experts. More information collected from aquaculture experts by country can be found in the Appendix.

Country	Finfish	Shellfish	Crustacean	Seaweed	Current offshore aquaculture operations	Expansion plans for offshore aquaculture	Suitability for ocean renewable energy
Australia	✔	✔	✔	✔	Yes	Industry planning for offshore operations	Yes
Belgium		✔		✔	Yes	Expansion plans in place	To be determined, dependent on operation but likely wave or solar photovoltaic
Canada	✔	✔			Yes		Yes
Chile	✔	✔		✔	No	The Chilean government and aquaculture industry intend to expand offshore finfish operations	Yes, but will depend; large potential for floating wind and wave energy
China	✔	✔	✔	✔	Yes	Currently working on expansion plans for offshore	Yes, very suitable
France	✔	✔	✔		No	Yes, but may be limited to shellfish within offshore wind farms	Yes, estuarine current energy suitable for shellfish
Ireland	✔	✔		✔	No	No plans to move offshore due to licensing backlog	Yes, but site dependent
Japan	✔	✔	✔	✔		Japanese government published an aquaculture growth strategy	Suitability is currently unclear
Norway	✔	✔	✔		Yes	Potential to move further offshore	Yes, wave energy possible

Country	Finfish	Shellfish	Crustacean	Seaweed	Current offshore aquaculture operations	Expansion plans for offshore aquaculture	Suitability for ocean renewable energy
Philippines	✔	✔	✔	✔	Very few	Selected sites and growers studying potential for offshore expansion	Yes, off-grid areas and some offshore aquaculture operations will be the first markets for ocean renewable energy (e.g., tidal currents, wave, and ocean thermal energy conversion)
Singapore	✔	✔	✔		Yes	Expansion plans in place. Using self-contained platforms may accelerate offshore expansion	Yes, selected sites with ocean renewable energy potential (e.g., tidal current, wave)
Spain	✔	✔		✔	No	Expansion plans in place	
United Kingdom	✔	✔	✔	✔	No	Extensive plans in place to increase production	Yes, wave energy possible
United States	✔	✔		✔	No	Government and industry planning for offshore expansion	Yes, wave energy possible; potential for tidal energy for nearshore operations

Information was reported for Ocean Energy System member countries, and a few non-member countries, that had available information about offshore operations, expansion plans, and/or suitability for ocean renewable energy.

3.2 Energy Needs of Aquaculture

A key component of advancing the co-location of ORE and offshore aquaculture is understanding the energy demands and energy-intensive resource requirements for different aquaculture operations. This information is crucial for developing appropriate renewable energy power systems for aquaculture and identifying feasible markets for these systems. Within the aquaculture sector, the energy-intensive resource demands can vary greatly by operation and species. Energy requirements include, but are not limited to, lighting, pumps, feeding, aeration, desalination, cleaning, refrigeration, monitoring, and support (barge) operations. Based on the species (e.g., finfish, crustaceans, shellfish, or seaweed), there may be different optimal power solutions to meet specific operational needs. Furthermore, based on site-specific requirements, energy needs may also vary by geographic location, even when farming similar species. Growing cycles, particularly for finfish, can also change the operational demand for energy over the year, such as the energy need for lighting during winter seasons (SARF 2014).

Overall, limited data are available from the aquaculture industry about specific energy needs, particularly for offshore systems. When available, data are often inconsistent, use different metrics, or are tracked by fuel consumption rather than by electricity usage. This report has gathered available energy information from marine-based operations to provide a picture of aquaculture energy requirements, including bulk energy demands per aquaculture operation and demand profile information where available.

3.2.1 Finfish Aquaculture

Finfish aquaculture includes a variety of equipment and operations which can lead to larger energy demands than for other farmed marine animals. In this section, energy demands for Atlantic salmon (*Salmo salar*) in Australia, Chile, Norway, and Scotland are reported as well as Asian seabass or barramundi (*Lates calcarifer*) in Singapore.

Atlantic Salmon

Atlantic salmon are farmed and grown for about 10 to 16 months in freshwater and are then transferred to the marine environment via specialized well boats, in which they are grown for 12 to 24 months (MOWI 2020). Upon completion of the grow-out period, the salmon are removed from the net pens and processed. This study presents the energy demands associated with the 1- to 2-year marine grow-out period that uses large sea cages or nets suspended from various floating systems that are anchored to the seabed (MOWI 2020). During this period, examples of energy use include, but are not limited to, lighting (both ongoing and intermittent), feed systems, net cleaning systems, and monitoring equipment.

Salmon aquaculture operations differ by country. For example, in Chile, grow-out operations generally range from 16 to 40 square cages with a typical 16-cage operation producing up to 4–5 tonnes of fish (Subpesca 2012). In Norway, the stocking densities and sea cage configurations are often varied across different farms. Although the offshore Australian Atlantic salmon sector is currently being developed, it is expected that these offshore farms will, in general, employ 12 sea cages, with each cage containing around 150,000 individual salmon (Hemer et al. 2020).

Australia

Aquaculture is Australia's fastest growing primary industry, and salmonids represent the largest aquaculture sector. Within Australia, the island state of Tasmania accounts for 98% of the salmonoid production (ABARES 2018). Currently, marine-based Atlantic salmon farming operations are predominantly based at sheltered nearshore sites. Increasingly, the sector is seeking to expand operations offshore into more exposed and energetic sites. Australian salmon operations are currently powered by diesel and electricity connected via the grid. While the production cycle for Australian Atlantic salmon is similar to that of other countries, it includes bathing and venturation (a process of raising dissolved oxygen levels in the water for fish health management purposes) operations that are unique to Tasmania. In Tasmania, amoebic gill disease is a gill disorder known to affect juvenile Atlantic salmon (Young et al. 2007). To prevent and mitigate the severity of this disease, whole sea cages are bathed in freshwater, despite this method being recognized as both expensive and technically difficult to achieve (Hemer et al. 2020). In addition to bathing, the sea cages undergo venturation in the summer months, a process that can operate 24 hours per day depending on environmental conditions.

A study led by the Blue Economy Cooperative Research Centre (BE CRC) in 2020 modeled the energy demands for an offshore salmon operation with an annual production of 10,000 head-on-gutted (HOG) tonnes (Hemer et al. 2020). This study estimated that energy inputs associated with transporting the various feed components and diesel for power generators onsite would be approximately 9,000 kWh/day. Additionally, the daily stationary electrical demands of feed barge operations, lighting, venturation, bathing, monitoring, and domestic use were estimated to total around 6,000 kWh/day (Hemer et al. 2020). A further breakdown of modeled energy requirements is presented in Figure 2, with detailed information about the average kilowatt-hour per day and percentage of total of daily energy use.

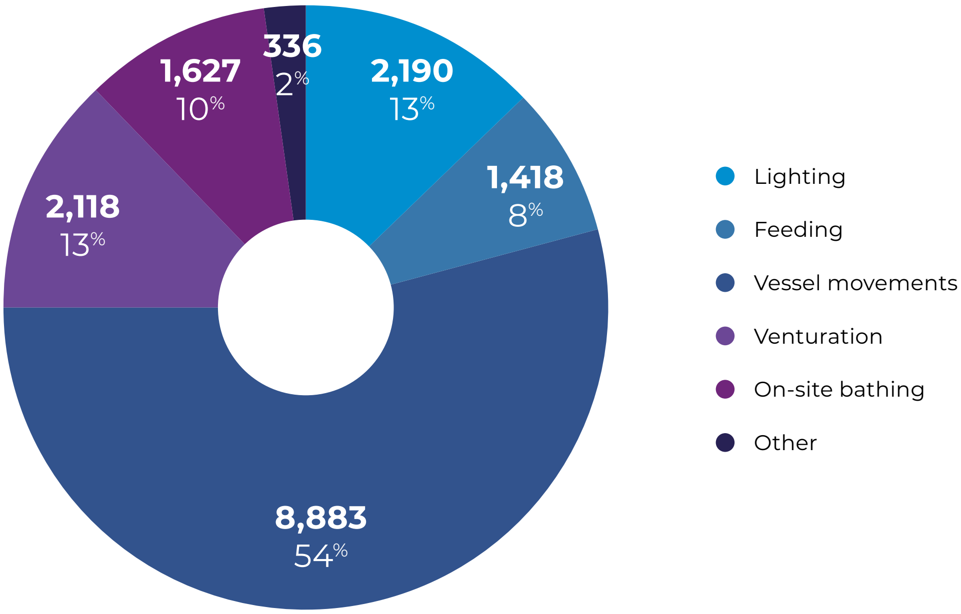


Figure 2. Modeled daily electrical energy requirements of an Australian Atlantic salmon offshore grow-out operation by kilowatt-hour (and percentage of total energy use). Data were modeled assuming 10,000 HOG tonnes/year (Hemer et al. 2020).

Chile

Salmon make up approximately 70% of the total production of aquaculture in Chile, which has about 330 active fish farms (SERNAPESCA 2020). Atlantic salmon produced in Chile spend between 14 to 18 months in the grow-out period at sea before they are harvested at weights between 4–6 kg. Finfish farms in Chile typically comprise floating net pens (pontoons) stocked with 8–17 kg/m^3 of fish. The energy demand of operations changes with fish growth, health requirements, and season, and differs by company. Because of this variation, Figure 3 represents a reference energy consumption for operations in Chile. The main generator that supplies power to productive and domestic activities has an installed power ranging typically between 100–250 kW. For domestic activities such as heating, hot water, water pumps, sewage, and other activities related to the permanent crew quarters, daily consumption varies between 35–115 kWh. Similarly, the seasonal variation of light availability and fish size results in different energy requirements for productive activities such as feeding and photoperiod operations, ranging between 130–450 kWh daily.

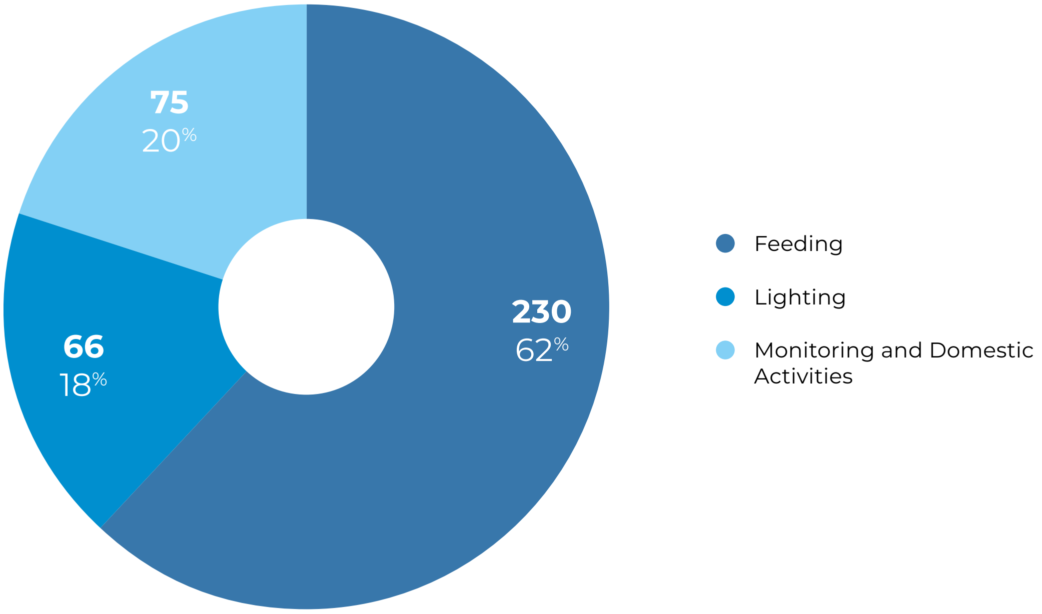


Figure 3. Average daily energy demand by operation for a Chilean Atlantic salmon farm by kilowatt-hour (and percentage of total energy use). Feeding, lighting, domestic activities, and monitoring energy estimates are averaged across the year to account for the seasonal demand for photoperiod and increased feeding operations. Energy consumption is based on a production capacity of 25,000–60,000 fish (or between 113–270 tonnes of salmon based on 222 salmon per tonne) and a cumulative energy demand of 371 kWh/day (pers. comm. Gonzalo Tampier, 2021).

Norway

In Norway, salmon farming is the second largest exporting industry; with 837 active farming locations in 2018 (Møller 2019). Some farms are grid-connected, while others rely on diesel generators to provide power to farm operations; for example, in one county on the central coast of Norway about half of the salmon farms are grid-connected (Møller 2019). A typical salmon farm includes nearshore net pens of various sizes and numbers, a feed barge, lighting, monitoring systems, living quarters, additional equipment, and two vessels (often a transport and a work vessel). Daily and seasonal energy consumption vary across salmon farms in Norway, as detailed by Syse (2016) and Møller (2019), who assessed the energy demands of salmon aquaculture in Norway.

Syse (2016) studied the electrical demands of three salmon aquaculture farms across southwest Norway. The farms used in this study ranged in size, using between 3 and 8 sea cages, and were stocked with 150,000 salmon per cage. Because the farms were grid-connected, hourly demand data were obtained from the electricity provider and the daily average electricity consumption was mapped across multiple components, excluding transport. The findings demonstrated that energy demand varied widely depending on operations carried out each day, the operational stage of the grow-out, and across different seasons. The feed system (feed barge compressor) was found to account for more than 50% of the daily energy use within the farms.

Møller (2019) mapped the energy demand across the entire Norwegian Atlantic salmon aquaculture industry using data from grid-connected and diesel-reliant farms. The results from that study highlighted energy variations based on the different operations and between seasons. The greatest point of difference in the energy profiles across summer and winter operations was the energy demand for cage lights and feed systems. Typically, there is no energy demand for cage lights in summer when daylight hours are extended, and a higher demand for lighting during winter when daylight hours are limited. In contrast, feed system energy demand is higher in summer when salmon are growing at a faster rate and require more feeding, compared to winter when there are lower feed requirements. The average cumulative energy demand across summer and winter operations was approximately 700 kWh/day, and Møller (2019) outlined an analysis of onsite energy demand to distinguish contributions (Figure 4). Operations were found to have an average energy demand of 0.35 kWh/kg of salmon produced (Møller 2019).

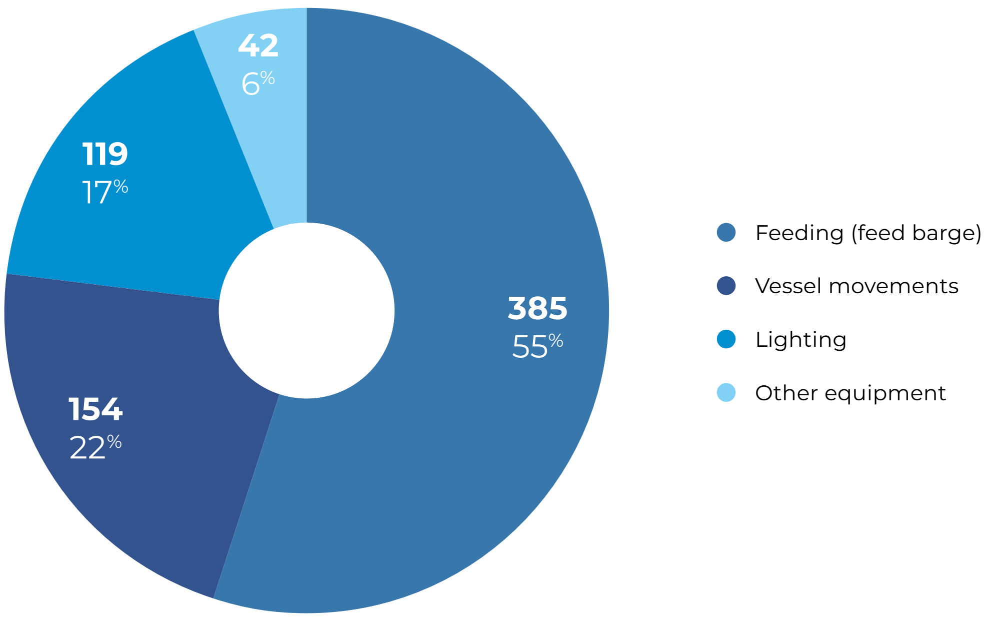


Figure 4. Daily energy demand profile for a Norwegian salmon farm by kilowatt-hour (and percentage of total daily energy use). Energy consumptions are based on a farm with a production capacity of 3,120 tonnes and an average cumulative energy demand of 700 kWh/day (Møller 2019).

Scotland

Energy requirements for salmon aquaculture in Scotland were gathered from several of the largest salmon farms (SARF 2014). Marine-based salmon sites, with average annual production volumes of approximately 1,000 tonnes (Marine Scotland Science 2021),[1] were reported to use on average 91 kWh/day for site offices and buildings and around 629 kWh/day (assuming a generator size of 150 kW with three-quarter load) for feeding, lighting, aeration, acoustic deterrents, monitoring, and other equipment (SARF 2014). This energy was typically provided by a generator on a nearby pontoon or feed barge. The peak load, including lighting, crew facilities, and other operations, was estimated to be 62 kW. Additional figures for the salmon industry, including hatcheries, freshwater loch cages, and processing facilities, are presented by the Scottish Aquaculture Research Forum (SARF 2014).

Asian Seabass/Barramundi

Asian seabass or barramundi are catadromous fish that grow rapidly, reaching a harvestable size (350 g–3 kg) in 6 months to 2 years (FAO 2009). Most barramundi operations use both floating and fixed net cages (Towers 2010). The cages range in size from 3 × 3 m up to 10 × 10 m and 2–3 m in depth. Most marine-based production of barramundi occurs in Southeast Asia, generally using small nearshore cage farms (Towers 2010). These farms often grow a mixture of species, including barramundi, grouper (Family Serranidae, Subfamily Epinephelinae), and snapper (Family Lutjanidae).

1 The 1,000 tonnes average production volume of salmon is an estimate based on the total salmon production of 236,000 tonnes across 232 sites in Scotland, as reported by Marine Scotland Science (2021).

Singapore

In Singapore, the Aquaculture Centre of Excellence has developed the Eco-Ark, a marine-based floating, closed system used to produce around 166 tonnes of fish per year (mainly barramundi) (Leow 2021). The Eco-Ark platform is 48 m x 28 m, automated, and comprises four tanks (500 m^3 each), each producing around 20 tonnes of fish per tank. Operations also include a nursery, two sea intake pumps, dissolved oxygen pumps, ice-makers, harvest preparation, monitoring equipment, domestic activities, and a post-harvest factory for packaging. Figure 5 details the annual energy demand of the Eco-Ark and demonstrates that the greatest daily demand is from feeding, which accounts for approximately 37% (3,500 kWh) of the total energy required (21,000 kWh/tonne of fish) (Leow 2021). Eco-Ark has a future target of 5,700 kWh/tonne that they aim to achieve in the next few years (Leow 2021).

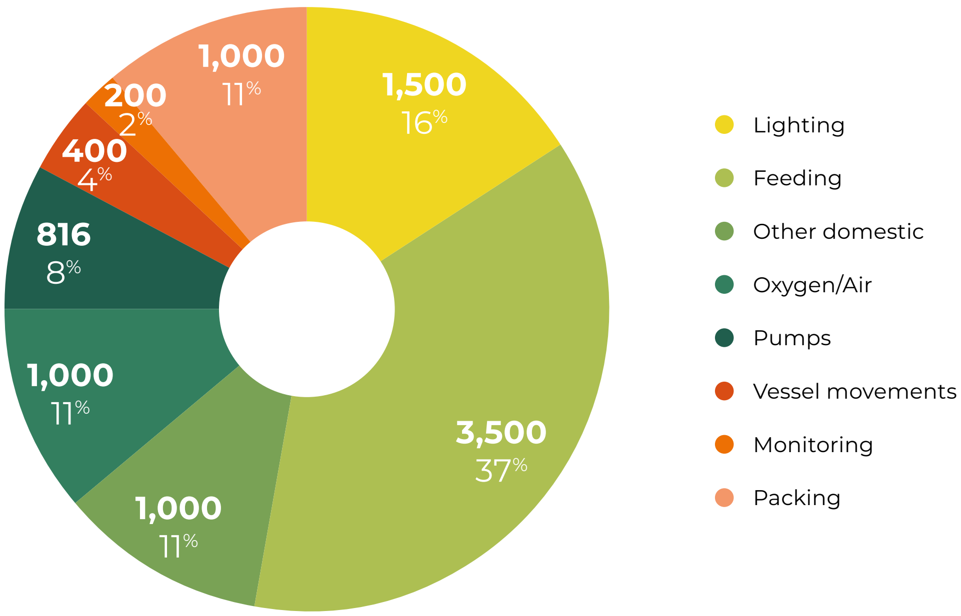


Figure 5. Average daily energy demand profile of the marine-based, enclosed system Asian seabass farm, Eco-Ark, in Singapore in kilowatt-hours (and percentage of total daily energy use) (pers. comms. Ban Tat Leow, October 2, 2021). The energy consumption is based on an annual production capacity of 166 tonnes and a cumulative energy demand of 9,416 kWh/day. The current bulk energy demand per tonne is 21,000 kWh/year (Leow 2021).

Singapore Aquaculture Technologies, with funding from the Singapore Food Authority, have developed a fish farm on the east coast of Singapore, called the Smart Floating Fish Farm. This facility consists of a 3,000 m^2 offshore, closed-containment, floating barge with 10 tanks that can produce up to 350 tonnes of fish annually, farming both barramundi and red snapper (*L. campechanus*) (Singapore Food Authority 2022). Operations include water treatment systems (filtration, oxygenation, etc.) and systems to monitor fish health and growth; and automation and artificial intelligence are used to aid aquaculture operations (Singapore Aquaculture Technologies 2022). Of these operations, a minimum of 50% are powered using solar PV units, which are mounted on the barge and include an energy battery storage system to achieve a stable power supply (Megawatts 2020). As an alternative to diesel fuel, this PV-battery system has allowed Singapore Aquaculture Technologies to generate energy onsite and, in turn, avoid buying and transporting fuel (Megawatts 2020). The bulk energy demand for the Smart Floating Fish Farm can be calculated assuming 0.2 kW peak power can be produced per square meter and using Singapore's baseline yield of 1,250 kWh/kW peak per year (Luther and Reindl 2014). Based on these assumptions and the 3,000 m^2 area of the farm, this would produce about 0.75 GWh/year of energy from solar PV supplying 50% of the power for an annual total energy requirement of approximately 1.5 GWh/year (0.75 GWh/year from solar PV and 0.75 GWh/year from other sources). Therefore, it is estimated the farm could have an annual energy demand of about 4,285 kWh/tonne.

3.2.2 Shellfish Aquaculture

Shellfish aquaculture operations are a bit more simplified than those for finfish, though they may still include a variety of equipment depending on the grow-out technique used. In this section, energy demands for oysters (*Crassostrea gigas* and *C. virginica*) are reported for Scotland and the United States and energy demands for blue mussels (*Mytilus edulis*) are reported for Scotland.

Oysters – Pacific Oyster and Eastern Oyster

Oyster production relies on the settlement of oyster larvae on a substrate (oyster shells, ceramic tiles, etc.) in a hatchery or in the wild (NOAA 2021). Once settled, oysters will grow within a farm for several months until they reach market size (i.e., adult stage). The grow-out duration varies depending on the food availability from the natural environment (SARF 2012). Based on environmental conditions (e.g., water depth, tidal range, bottom substrate), three methods can be used to farm oysters: off-bottom culture in the intertidal zone, on-bottom culture in the intertidal zone or in deep water, and suspended culture in the open sea (Buestel et al. 2009).

Scotland

Pacific oyster aquaculture in Scotland follows the traditional bag and trestle method with the oysters suspended near the surface of the water in baskets, trays, racks, or cages. Throughout their 3.5- to 6-year grow-out period, the oysters feed on the naturally occurring plankton and are continuously re-graded (i.e., sorted according to size) to optimize their growth. Once they are ready for harvest, the oysters are removed from the water, washed, sorted, graded, and transported to market (SARF 2014). The Scotland oyster farms assessed for this report use both electricity for seawater pumps, grading machines, lighting, and other services, and diesel for vessels and vehicles and generators (Figure 6). For this report, the liters of diesel reported by SARF (2012) were converted to kilowatt-hours to remain consistent with other examples presented in this chapter. It is assumed that 1 L of diesel fuel would be equivalent to 10.6 kWh (Krysinski and Malburet 2020).

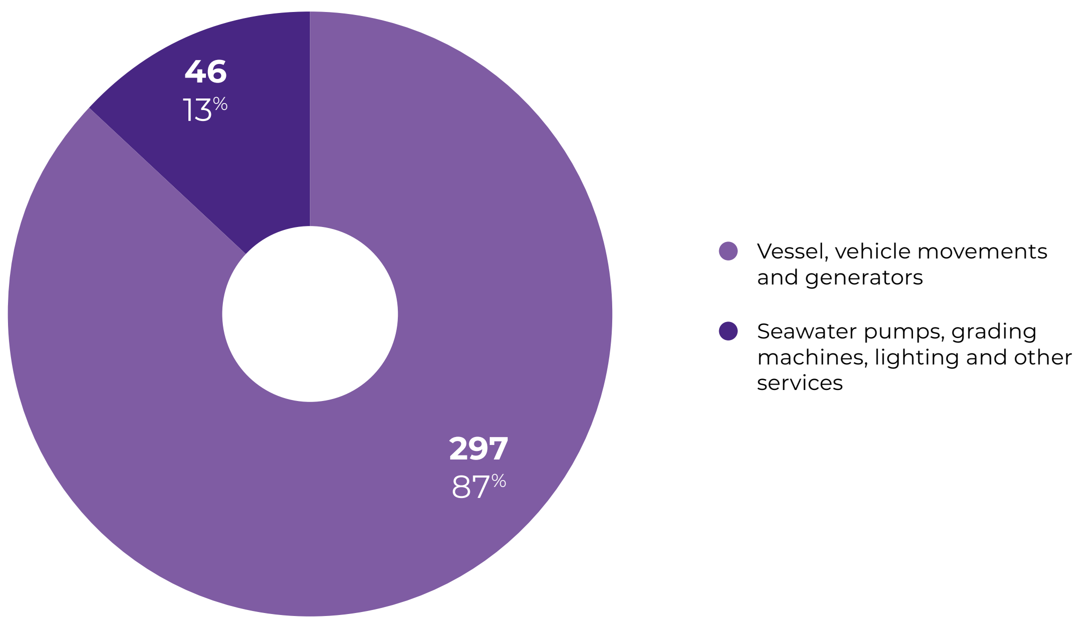


Figure 6. Annual energy demands for oyster farming in Scotland by kilowatt-hour (and percentage of total energy use). Energy consumption is based on oysters produced (per tonne) (SARF 2012).

United States

In the United States, Williamson et al. (2015) provided an assessment of two types of oyster farms—bottom cage cultures and floating rafts—on the east coast. Both farms are located within the Chesapeake Bay estuary and grow the native Eastern oyster. The bottom cage system grows oysters in cages placed on the seafloor, whereas the floating raft system grows oyster in mesh bags within buoyant, enclosed plastic pipes that float at the surface. The bottom cage operation is 23,216 m^2 in area and uses 2,000 cages that each can hold 1,500 to 3,000 oysters, with a stocking density of 194 oysters/m^2. The floating raft operation is 9,812 m^2 in area and uses 2,380 floating rafts with a stocking density of 153 oysters/m^2. The bottom cage operation uses a customized boat for harvesting and maintaining cages, nursery systems (both floating and onshore), process equipment (power-winch, tumbler, pressure washer), and a diesel fuel generator. The floating raft system, in contrast, does not use boats, a nursery system, or power winches because the oysters are grown close to shore along a pier and on the surface, eliminating the need for such equipment. The bottom cage farm was estimated to use about 5 kWh of electricity and 10 kWh of fuel and gasoline inputs annually per m^2, whereas the raft culture farm was estimated to use about 2 kWh of electricity and 0.4 kWh of fuel and gasoline inputs annually per square meter.

Blue Mussel

Scotland

The blue mussel (also known as the common mussel) is a widely distributed shellfish that is naturally occurring in intertidal regions of sheltered coasts, bays, and inlets as well as in tide-swept sheltered sea lochs (MarLIN 2008). In the United Kingdom, mussel farmers rely on the annual cycle of mussels to facilitate "rope grown mussels," which involves a process in which drifting mussel larvae attach to ropes suspended in the water. Once attached, the mussels remain there for 2 to 3 years before they reach marketable size and are harvested. While stocking capacity may differ, generally a rope that is 200 m long can grow up to 30 tonnes of blue mussels. The energy demands of blue mussel farming are significantly less than other aquaculture operations. A study in 2011 indicated that the energy consumption for blue mussel aquaculture typically includes diesel for vessels, vehicles (forklift), and generators, as well as electricity for seawater pumps, a grading machine (unless stationed on the vessel), and general lighting and services (Figure 7; SARF 2012).

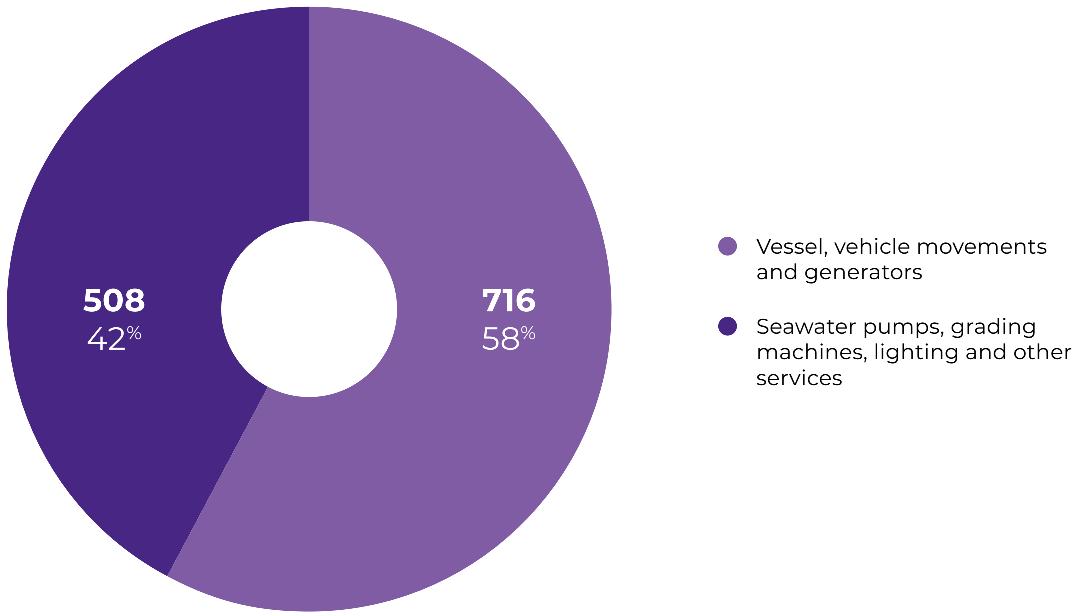


Figure 7. Annual energy demand for blue mussel farming in Scotland by kilowatt-hour (and percentage of total energy use). Energy consumption is based on mussels produced (per tonne) (SARF 2012).

3.2.3 Aquaculture Energy Demand by Species and Country

Figure 8 summarizes the energy demand (kWh/tonne) for several farmed aquaculture species across countries based on the numbers presented in Sections 3.2.1. and 3.2.2. and standardized by kilowatt-hours/tonne per year for comparison.[2] The summary of energy per standard weight of product (kWh/tonne) per year is a useful metric for better understanding the energy demand of different aquaculture operations and assessing the variability. As Figure 8 demonstrates, there is a notable difference in the energy demand across countries that farm the same species (as shown for salmon and oysters) and across farmed species. The differences across countries may be explained by practices. For example, the energy demands for Australia salmon operations were modeled after an offshore farm compared to the nearshore farms of Chile, Norway, and Scotland that may require less energy, such as fuel. The differences in energy demand across species reflect the different operational needs and the variability of operations reported (especially when vessels are included in the energy demands). For barramundi aquaculture in Singapore, the high value reported is due to the large energy demands of the Eco-Ark and the Smart Floating Fish Farm. Both operations include automated systems and the need for water filtration and sterilization because they are closed-containment aquaculture systems. The Eco-Ark also has a nursery and a post-harvest factory in addition to grow-out and harvest operations. Some of the energy demands for oyster and mussel aquaculture are unexpectedly higher than for finfish aquaculture. This difference may be explained by the vessels use included in all shellfish operations compared to salmon farms, that do not all include vessel use. Gaining a more detailed, finer-resolution understanding from a wider diversity of aquaculture farms and having reports on all operations and systems will help shed light on these differences. Further research is needed on estimating energy demands across farmed species and countries, including using standard units, to allow for more confident comparisons across aquaculture operations. This will also aid in understanding which type of aquaculture is best paired with which ORE technology.

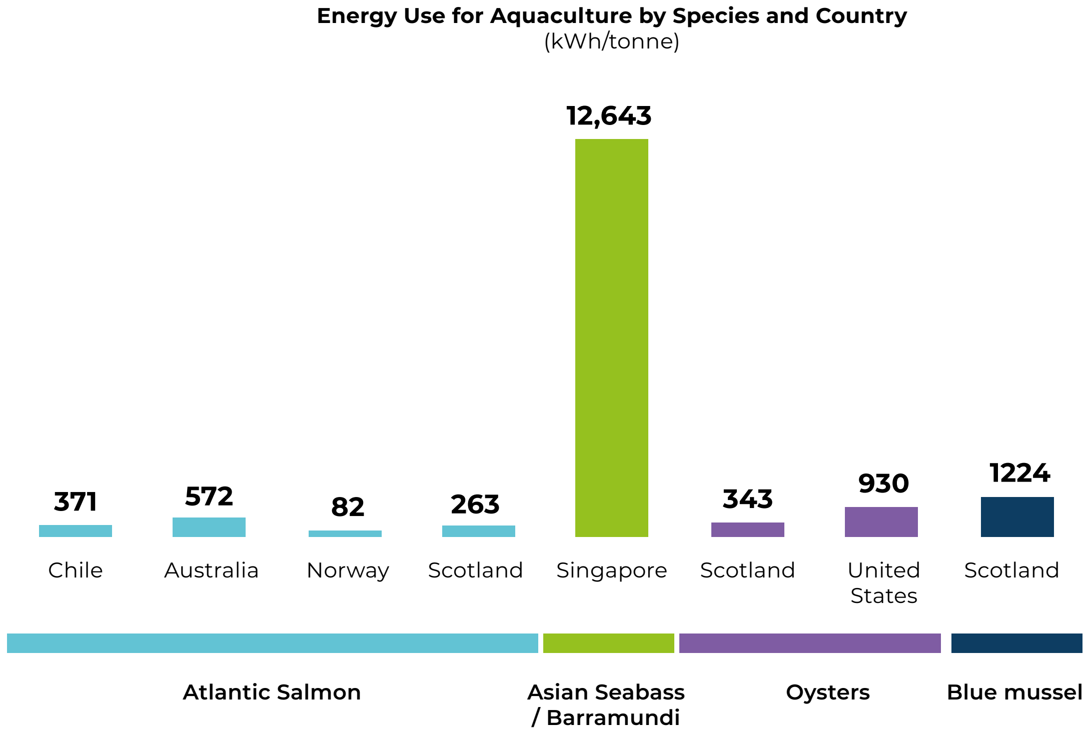


Figure 8. Comparison of the yearly annual energy demand per tonne (kWh/tonne) of aquaculture product across finfish and shellfish operations. Aquaculture operations considered in this analysis vary for each species and country. For example, Australian Atlantic salmon, Singapore Asian seabass, oyster, and Scotland blue mussel all include energy demands for vessels, whereas Chile, Norway and Scotland Atlantic salmon do not.

2 For countries where energy demands were available for more than one aquaculture operation per species (Singapore barramundi and United States oysters), the energy information for the two operations were averaged to report one number for Figure 8.

4.

CO-LOCATION CASE STUDIES AND LESSONS LEARNED

As mentioned in previous chapters, the development of co-located aquaculture and ORE can help aid the continued expansion of the global aquaculture industry. Synergistic opportunities for co-located aquaculture and ORE can provide a multifunctional use of space and resources. This chapter includes summaries of 12 case studies across 5 OES countries (Australia, China, France, Singapore, United States,) and 3 non-OES countries (Cabo Verde, Scotland, Wales), exploring past and present aquaculture projects that have used ORE, solar PV, offshore wind technologies, or hybrid solutions to meet energy demands (Figure 9). These case studies include all marine-based aquaculture types (finfish, shellfish, crustacean, and seaweed; onshore, nearshore, and offshore) and a diverse range of renewable energy technologies, with a focus on ORE, to provide examples and lessons learned for co-locating ORE and offshore aquaculture.

WEC
1. Albatern and Marine Harvest
2. MARIBE
3. SINN Power
4. Aquapower Technologies
5. Carnegie Clean Energy
6. BLUE DEAL Med

OTEC
7. Hawaii Ocean Science and Technology Park

Hybrid
8. Penghu
9. Multi Level Floating Platform
10. ERSEO

Solar PV
11. Copper Beech Farm
12. Eco-Ark

Figure 9. Geographic distribution of aquaculture and renewable energy case studies. The color of pins represents the renewable energy technology used within aquaculture operations: orange represents wave energy converters (WEC), yellow represents ocean thermal energy conversion (OTEC), green represents hybrid, and red represents solar photovoltaic (PV).

Wave Energy

Albatern and Marine Harvest Scotland
Offshore finfish aquaculture and wave energy – Scotland

Through a collaboration between Albatern and Marine Harvest Scotland, a 14-week pilot study in Scotland was undertaken to assess the potential for wave energy to power offshore finfish aquaculture operations. Two Albatern WaveNET arrays, known as SQUID generating units, were deployed off the Isle of Muck in 2013 (Campbell 2017). The WaveNET is a floating, array-based WEC that tracks the orbital motion of fluid particles, capturing energy as it moves with the motion of the waves and converting it to electricity, and it is configurable to match site and power requirements. For example, increasing the length of the array can capture more energy from longer waves, and increasing the width of the array can capture more energy from lower density sites (Campbell 2017). SQUID generating units have a rated capacity of 7.5 kW and can be scaled up with modules rated up to 750 kW and deployed in arrays of over 10 MW in capacity (Paschoa 2011). The Isle of Muck project demonstrated nonlinear energy yield enhancements in the array, improving the economy of future wave technology development, and reduced the costs of deploying and maintaining the array by using small recurrent components to build the large array (Campbell 2017). Lessons learned from the project were the high survivability of the SQUID generating units during large wave events, the reliability of the WaveNET arrays irrespective of individual component or device failures, and the high cost of the technology prototypes that became a challenge regarding funding.

In 2015, the positive outcomes from the Isle of Muck project led to another deployment of the WaveNET in Mingary Bay on the west coast of Scotland, to power an active offshore fish farm site owned by Marine Harvest Scotland. The marine license and seabed lease applications took about 6 months to acquire, and involved several groups of stakeholders, including fishermen who voiced some concerns. As a mitigation measure to avoid any potential risk to the fish farm, the power generated from the WaveNET was transmitted to a shore station, and then to the fish farm barge via a cable. Campbell (2017) stated that the reliability of the electrical systems onshore was a challenge for Albatern in this project and the possibility of adding storage was being investigated. Updates on this project are not available currently.

MARIBE
Offshore seaweed aquaculture and wave energy – Wales

Wave Dragon and Seaweed Energy Solutions worked collaboratively on the Marine Investment for the Blue Economy (MARIBE) project, which aimed to combine wave energy and seaweed production offshore. Using an array of WECs, the overtopping technology of Wave Dragon will harness the energy of waves and may act as a buffer and, in turn, create an area with reduced waves that is suitable for farming seaweed (MARIBE 2016). Wave Dragon is a scalable, floating WEC developed to operate in intermediate water depths of 30 m and deeper. The central front face of a Wave Dragon device is a doubly curved ramp, that allows incoming waves to surge up the ramp, and a reservoir collects the water that overtops. The water in the reservoir is then drained back into the sea, with energy extracted as the water passes through multiple low-lead hydro turbines during the draining process. Wave Dragon's long mounted reflector arms allow the device to turn into the principal wave direction, increasing the amount of energy that is captured (MARIBE 2016; State of Green n.d.). In this project, the proposed Wave Dragon WEC would be a 4 MW device producing up to 12 GWh/year. Wave Dragon plans to continue efforts to deploy a pilot wave energy and offshore aquaculture system in the future.

Wave Dragon overtopping wave energy converter (image courtesy of Wave Dragon).

SINN Power
Shrimp and prawn aquaculture and wave energy – Cabo Verde

Renewable energy developer SINN Power and local aquaculture firm Fazenda de Camarão started a collaborative project that aimed to assess the feasibility of using wave energy to power local shrimp farm operations in São Vicente, Cabo Verde. During the preliminary stages of the project, SINN Power measured local wave data, produced wave profiles, and worked with the aquaculture operators to develop a prototype. The SINN Power point absorber WEC has been developed to generate electrical energy as the 10 m lifting rod is raised by the motion of the waves. It has an installed power capacity of 36 kW within a 10 m^2 area and can be installed in offshore, open environments, as well as on fixed platforms and structures (Offshore Energy 2018a). Upon completion of the preliminary research, SINN Power aimed to provide a customized off-grid power system tailored to the shrimp farm. This project is in line with the island country's plans to obtain 100% of its electricity from renewable energy by 2025 (Davis 2018). Currently, there is no information about the continuity of this project.

Aqua Power Technologies
Nearshore finfish aquaculture and wave energy – Scotland

Aqua Power Technologies' 4.6 kW MANTA is a submersible wave energy device specifically designed for remote installations, including offshore fish farms (Aqua Power Technologies Limited 2022). MANTA is a small and low-cost WEC intended to be installed in arrays. Deployed at depths between 10 to 20 m, MANTA has large hydrodynamic "wings" that move up and down, using the power of the waves to generate electricity and charge battery banks. The battery banks are then used to power offshore operations, including computers, lights, communication systems, sensors, and desalination units. In 2018, a single MANTA WEC was installed in Scottish Sea Farms' Teisti Geo finfish farm in Clift Sound, Scotland. Installation of the MANTA device did not require additional licensing because it was sited within the already-consented area of the salmon farm (pers. comm. Sam Etherington, February 22, 2022). The MANTA device was installed for 18 months, during which it produced more than 11 MW of power, and a number of different power profiles were tested (pers. comm. Sam Etherington, February 22, 2022). During this test deployment, Scottish Sea Farms maintained use of their generators, but used the WEC to feed into their system for low-power operations. This project by Aqua Power Technologies and Scottish Sea Farms aimed to determine the opportunities associated with ORE in the region, assess the feasibility of using the MANTA to produce consistent energy throughout the year, and reduce Scotland's reliance on diesel generators (Offshore Energy 2018b). The project ended in 2020. Aqua Power Technologies is continuing efforts to provide power to aquaculture systems.

Aqua Power Technologies MANTA wave energy device installed at a Scottish salmon farm (image courtesy of Aqua Power Technologies).

Carnegie Clean Energy
Offshore aquaculture and wave energy – Australia

The Carnegie Clean Energy project, MoorPower™, was developed in collaboration with BE CRC and industry partners in 2021. This 3-year project includes a design, installation, and operational phase to create a novel WEC system for use in offshore environments. The MoorPower wave converter system is intended to secure clean and reliable energy, replacing the diesel generators that would otherwise be used in operations that cannot access shore-based power. The primary market for MoorPower would be energy-intensive offshore aquaculture operations, such as feed barges, and diesel-powered vessels that require energy for electrical loads operating offshore. The technology is based on the design principle of Carnegie's CETO point absorber WEC buoys (Carnegie Clean Energy 2022a). The CETO buoys are submerged a few meters below the surface of the ocean, where the device moves with the motion of the waves (Carnegie Clean Energy 2022a). This orbital motion drives a power take-off system that converts the physical motion of the device into electricity. Carnegie's latest iteration of the CETO buoy, CETO 6, is planned to have a power capacity of 1.5 MW per buoy (Carnegie Clean Energy 2022b). The current 3-year project will see the deployment of a demonstration MoorPower wave energy device offshore of the Carnegie research facility, in North Fremantle, Western Australia.

Carnegie's MoorPower wave converter system (image courtesy of Carnegie Clean Energy).

BLUE DEAL Med
Finfish aquaculture and wave energy – Cyprus

As part of the BLUE DEAL Interreg Mediterranean Project, BLUE DEAL Med is creating opportunities to promote the Blue Energy sector by creating connections among industries, governments, and institutions (BLUE DEAL Med 2022a). One aspect of BLUE DEAL Med is an Open Innovation Challenge to incorporate ORE and aquaculture (BLUE DEAL Med 2022b). Levantina Fish Ltd. currently operates two European seabass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) grow-out farms in the gulf of Limassol both with their own feeding platforms. One farm is located at 20 m depth and uses the SILO platform, which is bottom-mounted with an electrical generator that uses 132 kWh of energy, and another farm is located 1.5 km southeast and uses the FISH FEEDER floating barge platform with an electrical generator and a diesel engine that uses 160 kWh of energy (BLUE DEAL Med 2022b; BLUE DEAL Med 2022c). Levantina Fish Ltd. is committed to sustainable fish farming and, in addition to their Friend of the Sea's Sustainable Aquaculture Certification, they are currently looking to integrate ORE into their feeding platforms via BLUE DEAL Med's open call to ORE developers. As of late 2021, they had received seven proposals, six of which are for wave energy devices. One proposal from Resen Waves would employ their Smart Power Buoy that provides power and can facilitate data communication and automated/remote monitoring (Resen Waves 2021). Resen Waves estimated the SILO would require a WEC of 12 kW nominal power with a 150 kWh battery pack and the FISH FEEDER would require a WEC of 15 kW nominal power with a 190 kWh battery pack (BLUE DEAL Med 2022c). The wave buoy is well suited for offshore environments, would be situated independent of the aquaculture farms, and would be tension-moored to the seabed, providing power to a battery pack that can be located on the seabed or attached to the net pens.

Resen Waves' Power Buoy (image courtesy of Resen Waves).

Aerial view of Hawaii Ocean Science and Technology Park (image courtesy of the Natural Energy Laboratory of Hawaii Authority).

OTEC

Hawaii Ocean Science and Technology Park Onshore aquaculture and OTEC – United States

The Hawaii Ocean Science and Technology (HOST) Park is a research facility that uses sustainable and innovative ORE to support approximately 80% of the state's aquaculture and marine production (Deringer 2018). The HOST Park was founded in 1974 by the Natural Energy Laboratory of Hawaii Authority. Over time, the park has expanded to cover an 870-acre area with more than 50 tenants using the facility for scientific research, energy and ocean technology research and development, conservation, food production, water desalination, cooling, and aquaculture operations. The HOST Park is designed to take advantage of the ocean-bound nature of Hawaii, with site operations powered using a range of renewable energy technologies, including OTEC. The temperature difference between the warm surface waters and the deep ocean waters is greater than 20°C, making Hawaii an ideal location for OTEC. Within HOST Park, several OTEC projects were developed including a closed-cycle OTEC system to use the warm, surface-level waters to convert anhydrous ammonia from a fluid into a gas. From there, the cold water was used to convert the gas into a liquid, which was then recycled back through the system. This functioning prototype for a large scale commercial OTEC generated 105 kW and was integrated into the grid. After fulfilling its research and development purpose, it was decommissioned due to high operating costs. The data collected from this project has formed the basis for a variety of new heat exchanger projects that aim to reduce the operating costs for OTEC through miniaturization of the heat exchangers. The seawater distribution system that feeds into the OTEC projects also provides cold, deep, nutrient-rich water which supports the healthy production of numerous onshore aquaculture production sites, including those for crustaceans, microalgae, and shellfish. Solar PV is also being used as another renewable source of power within the HOST Park to power microalgae production.

Penghu aquaculture platform (image courtesy of Guangzhou Institute of Energy Conversion Chinese Academy of Sciences).

ORE and Solar PV

Penghu
Offshore finfish aquaculture and wave energy with solar PV – China

With government support for using ORE for aquaculture in China, the Guangzhou Institute of Energy Conversion Chinese Academy of Sciences developed a WEC power system—Sharp Eagle—designed for offshore aquaculture. The WEC integrated with the aquaculture platform "Penghu" was deployed in 2019 (Ma et al. 2022); 60 kW of wave energy and 60 kW of solar energy provide power for crew quarters, automatic bait casting, monitoring, fish transmission, ice making, and other production equipment, including seawater desalination. The at-sea trials have been successful and have shown that a 50–100 kW WEC can fulfill the energy needs of a 10,000–20,000 m^3 offshore cage (OES 2021c).

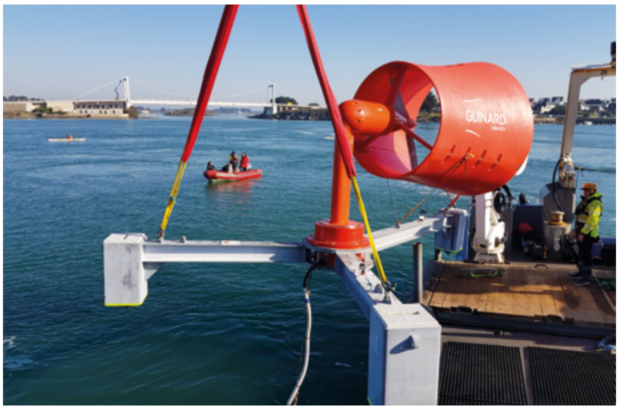
Multilevel Floating Farm
Offshore aquaculture and agriculture with solar PV, tidal energy, and wave energy – Singapore

The multilevel floating farm (MFF) concept integrates previous efforts of floating farming methods into a single consolidated unit with accommodation for many types of farm products (Asgarov et al. 2020). The MFF combines many basic modes of farming, including aquaculture for finfish, aquaponics for vegetables, and agriculture for soil-based products such as mushrooms. Each level of the MFF is focused on a distinctive farming type. For example, lower levels would be dedicated to aquaculture products; mid-levels would be dedicated to products requiring low light, such as mushrooms, eggs, and poultry; and higher levels with more direct access to sunlight would be dedicated to leafy greens and other vegetables such as tomatoes. The key challenge for the MFF is power; it has an annual projected demand of 22,210,000 kWh/year or about 61,000 kWh/day (Asgarov et al. 2020). Solar energy (via rooftop PV panels) is being considered as an option for power generation. However, it would only support about 3–5% of the energy demand. A marine area of more than 9 hectares covered by floating solar PV would be needed to power the MFF—an untenable scenario. ORE options (including tidal current and wave energy) are being studied in Singapore to hybridize the energy system and potentially improve the financial operating metrics of the MFF.

River Current and Solar PV

ERSEO
Nearshore oyster aquaculture and river current with solar PV – France

Since 2020, Guinard Énergies Nouvelles has developed the Énergies Renouvelables au Service des Exploitations Ostréicoles (ERSEO) project to provide renewable energy for oyster farms. The company has been investigating the energy needs of oyster farms in the northwest of France. Guinard Énergies Nouvelles tested and validated their 20 kW P154 tidal turbine for this application in an estuary environment in 2019 (FARNET 2021). In the ERSEO project, the second trial test to power an electric oyster barge with a coupled solar PV–river current turbine will occur in 2022. From the information collected during the project, recommendations for reducing energy use and developing renewable energy to power each farm will be provided.



Guinard Énergies Nouvelles's P154 tidal turbine being installed in Ria d'Etel (image courtesy of Guinard Énergies Nouvelles).

Solar PV

Copper Beech Farm
Oyster aquaculture and solar PV – United States

Copper Beech Farm and Roger Williams University designed and implemented an off-grid PV solar system for aquaculture use. This off-grid, renewable energy installation combines PV solar panels, battery storage, and a Floating Upweller System (FLUPSY)—used to increase water flow for aquaculture grow-out—to promote accelerated shellfish growth (Palano 2013). The installation consists of six mounted 245 W PV solar panels, an electrical distribution box, a charge controller that transfers the current from the PV solar panels to the nine 12 V battery bank, a 1/3 horsepower direct current motor, a belt, a shaft, and a propeller. The off-grid setup has been successful in providing enough power to operate the FLUPSY, and the battery bank has the capacity to power operations for 3 days without requiring any recharge from the PV solar panels (Palano 2013).

Eco-Ark
Nearshore finfish aquaculture and solar PV – Singapore

The Eco-Ark is an existing nearshore structure currently operational in Singapore. The Eco-Ark is a purpose-built, floating, closed-containment aquaculture system that covers an area of about 1,400 m^2. It requires only two workers and demonstrates the practical application of a floating closed-containment system for fish farming. There are four fish grow-out tanks with a combined 475–500 m^3 capacity, plus 30 additional nursery tanks each having 6.5 m^3 capacity. Production is about 166 tonnes of seabass per year, based upon two completed harvest cycles. Currently, rooftop solar panels supply about 352–440 kWh of the about 9,416 kWh total average energy requirement per day (pers. comm. Ban Tat Leow, October 2, 2021). The balance of the energy needed is currently supplied by diesel generators. The next step in the immediate future includes the installation of a "power barge" composed of floating solar PV units that will increase the use of renewable energy in the fish farm's operations.

Eco-Ark aquaculture system (image courtesy of Michael L.S. Abundo).

Lessons Learned from Case Studies

Some lessons learned can be extracted from these case studies. One of the main challenges to pursuing research or pilot projects is the lack of funding and the high cost of renewable energy technologies. In addition, while ORE devices are in their early stages of powering aquaculture operations, farms are likely to still need to employ their generators to avoid any issues with intermittency or security of supply until this novel application of ORE devices can be better understood. Consenting (or permitting) and regulatory processes for gaining approval to deploy an ORE device in situ are also often long and costly, though this may be eased by deploying an ORE device within an existing aquaculture site. Uncertainty among stakeholders remains relative to the effects of a device on the aquaculture system and the animals farmed. However, mitigation measures can be taken to prevent or reduce any adverse environmental effects of ORE.

These case studies highlight several projects, both past and present, that are conducting research on or have successfully implemented renewable energy to meet identified energy demands of finfish, shellfish, crustacean, or seaweed aquaculture. A number of these projects are currently in situ and have demonstrated the success and overall viability of delivering consistent power for operations, including wave energy for finfish aquaculture, OTEC for onshore aquaculture, and solar PV energy for both finfish and oyster aquaculture. Other projects are in planning phases and more updates should be available in the coming years about potential lessons learned, including wave energy for seaweed and shrimp/prawn aquaculture; wave, tidal, and solar PV use for the MFF agriculture and aquaculture system; and river current and solar PV use for oyster aquaculture.

5.

OPPORTUNITIES AND CHALLENGES FOR ORE AND OFFSHORE AQUACULTURE

Although both offshore aquaculture and ORE are relatively new industries, opportunities and challenges related to combining these marine uses can be identified from previous research projects, such as multi-platform or multi-use studies; analogous industries; and case studies from marine-based aquaculture, such as those detailed in Chapter 4. This chapter also highlights potential opportunities and challenges for co-location in several countries based on current or planned efforts.

5.1 Opportunities

By moving away from coastal waters, offshore aquaculture can reduce its impacts on marine ecosystems, decrease the potential for stakeholder conflict, and contribute to the growth of the seafood sector (Buck et al. 2018). With aquaculture operations requiring energy to power standard safety equipment, fish feeders, seawater pumps or aeration, lighting, mechanical equipment (regrading machines, cranes, etc.), refrigeration, marine sensors, and/or domestic activities for a crew, there are synergistic opportunities for co-locating offshore aquaculture and ORE (LiVecchi et al. 2019). Benefits are diverse and may include the following:

- Increased potential for co-location because offshore aquaculture is likely to be in higher-energy environments where ORE may be more feasible;
- Cost savings on energy use by providing power at sea, especially because diesel costs are likely to increase with distance to shore;
- Cost savings by shared operations and maintenance, including installation of system and monitoring operations;
- Synergies or shared structural support with cables, anchors, offshore platforms, and vessels (SARF 2014);
- Potential to use ORE to power autonomous and automated systems (e.g., oceanographic sensors, control of remote operated vehicles, and autonomous underwater vehicles) as operations move farther offshore (Gardner Pinfold Consultants Inc. 2019);
- Ability to minimize environmental effects in terms of lower greenhouse gas emissions and reduced potential for pollution from oil/fuel spills by using clean energy (Schultz-Zehden et al. 2018);
- Potential for reduced environmental effects (e.g., nutrient pollution, disease/parasite load, etc.) by moving offshore to more energetic sites viable for ORE (Froehlich et al. 2017);
- Reduced noise compared to diesel generators that may lessen impacts on the marine ecosystem;
- Low visibility of ORE devices paired with offshore aquaculture;
- Decreased conflict within and impact on coastal areas as aquaculture moves to offshore sites with less competition for space and resources; and
- Excess power from ORE could provide power to the grid or to onshore marine aquaculture facilities (such as hatcheries).

Combining ORE and aquaculture or other marine uses can also lead to the sustainable and efficient use of ocean space. In recent years, several research initiatives and projects have been undertaken to reduce spatial pressure by employing multi-use platforms (Schultz-Zehden et al. 2018). Zaucha et al. (2016) define multi-use platforms as the "joint intentional use of resources in close geographic proximity. This can involve a single user or multiple users." Multi-use platforms can include several combinations of marine uses (e.g., fisheries, aquaculture, tourism, ocean energy, etc.) and are characterized by the sharing of the same resources. For instance, multi-use platforms can integrate ORE and aquaculture operations with other uses. One example is tourism, which has been considered by exploring the benefits of implementing diving or snorkeling in proximity to or within aquaculture operations or sport fishing next to a farm (Schultz-Zehden et al. 2018). In addition to aiding tourism, this can also provide an alternative income for aquaculture developers. For the multi-use studies in this section, those considering renewable energy do not necessarily address providing power to the other use, but rather focus on assessing the shared use of space. Several projects on offshore multi-use platforms have been developed in Europe:

- The TROPOS project was funded in 2012 for 3 years by the European Commission (CORDIS 2019). This project aimed to develop a floating modular multi-use platform system in deep waters that integrated transportation, renewable energy, aquaculture, and tourism. Locations for development were identified for different scenarios such as wind energy and aquaculture in Crete, tourism and solar energy in Gran Canaria, and transport and offshore wind energy in the United Kingdom. Outcomes of the project were the development of methodologies to conduct impact assessments and to aid decision-making.
- The MERMAID project was funded in 2012 for 4 years to assess different concepts for the next generation of offshore multi-use platforms for energy extraction, aquaculture, and platform-related transport (CORDIS 2016). Case studies were completed in the Atlantic Ocean, Baltic Sea, Mediterranean Sea, and North Sea. Stakeholders (such as companies, agencies, researchers, and nongovernmental organizations) participated in the development of the platforms' design (van den Burg et al. 2016). All designs included offshore wind as energy sources, and WECs were also used in the design of the Atlantic site. Guidelines were developed within the project for the safe management of multi-use platforms and stakeholder involvement during the design process. It was found that the selection and planning methodologies of a site were transferable between locations, but the use of technical methodologies was site specific and strongly dependent on social components and licensing regulations.
- The Multi-Use in European Seas (MUSES) project was funded by the European Union's Horizon 2020 research and innovation program and was completed in 2018 (MUSES 2022). The project aimed to explore the opportunities for multi-use platforms in the Baltic Sea, Black Sea, Eastern Atlantic Ocean, Mediterranean Sea, and North Sea. The feasibility of various multi-use combinations, such as tourism and aquaculture, offshore wind and aquaculture, and wave energy and aquaculture, was analyzed. Project outcomes showed that the main driver for combining wave energy and aquaculture was the potential reduction in initial investment requirements for both developers due to shared operational and maintenance costs (Schultz-Zehden et al. 2018).
- MARIBE was funded in 2015 under the Horizon 2020 program to promote growth and jobs within the blue economy by sharing marine space (MARIBE 2018). Several case studies were developed to identify "Blue Growth" sectors. The case study on combining offshore finfish aquaculture and wave energy highlighted several advantages: achieving cost savings related to energy delivery, storage, and supply; enabling aquaculture farms to be farther offshore in nutrient-rich environments; limiting environmental effects by moving offshore; and guaranteed sale of electricity to the aquaculture customer.
- The UNITED project was funded in 2020 to demonstrate business synergies and benefits of ocean multi-use, and to provide a roadmap for future developments (UNITED 2022). The activities for this project are based on five multi-use pilot sites, three of which combine renewable energy and aquaculture: blue mussel and seaweed aquaculture and offshore wind in Germany; offshore seaweed and floating solar in the Netherlands; and flat oyster and seaweed aquaculture and offshore wind in Belgium. An additional pilot will explore the combination of offshore aquaculture and tourism in Greece. The UNITED project is currently active and will continue until 2023.

Some of the main benefits of co-locating offshore aquaculture and ORE are the collective use of space; the ability to share equipment, systems, and operations; and reduced environmental effects from using a sustainable source of energy that can be provided at sea. Co-locating offshore aquaculture and ORE can also help resolve infrastructure issues and the reliability of power supply, particularly in remote and isolated areas such as islands, where there is often a lack of electrification. This would also improve energy security in such areas that are often affected by climate-driven events. As more aquaculture operations use ORE, there could also be an opportunity to label aquaculture products originating from sustainable renewable powered operations (for example through Aquaculture Stewardship Council or Friend of the Sea certifications), thereby increasing their market values (Schultz-Zehden et al. 2018).

5.2 Challenges

While moving aquaculture farther offshore may present opportunities for co-location with ORE, it may also introduce some challenges. Because ORE is often intermittent, energy storage systems are needed onsite. However, storage of energy onsite may be difficult because of limited space on the aquaculture platform. Safety risks may be increased with offshore operations because they will be located in higher-energy and more exposed environments, which may lead to added costs and challenges for obtaining insurance (Schultz-Zehden et al. 2018). To advance the industries to full-scale ORE-aquaculture operations, pilot and demonstration projects are needed but they can be costly. The difficulty to secure adequate funding for such projects can provide a barrier to technology advancement and could hinder both industries as they strive to progress.

In the European MERMAID project, several challenges for combining aquaculture and energy at offshore sites were described (Christensen et al. 2015):

- Limited available technologies to prevent systems failure due to offshore wave climate;
- High cost of offshore equipment inducing limited investment;
- Stakeholder concerns related to environmental effects (e.g., pollution, fish escape from nets) and visual impacts of offshore aquaculture; and
- The potential for unclear and/or long licensing and consenting procedures.

A challenge for using ORE for smaller aquaculture operations, such as for shellfish or seaweed production, may be the low energy requirements. While there may be opportunities to power lower-energy operations as shown in the case studies in Chapter 4, doing so may be location- and operation-specific. The use of ORE for offshore aquaculture is likely better suited for finfish aquaculture, which has larger energy demands due to the various equipment and systems that require power. Because offshore finfish aquaculture will require continuous power to keep fish alive or maintain refrigeration, most ORE devices will need backup batteries and possibly generators, which may involve additional associated costs. ORE could also be feasible for integrated multi-tropic aquaculture (i.e., farming multiple species such as finfish, shellfish, and seaweed in one system), another developing sector of the aquaculture industry, but more information is needed about the energy requirements of these systems. For all aquaculture, more information is needed about energy demands to fully understand and mitigate challenges and increase the opportunities for using ORE.

Overall, for all types of ORE, a key barrier to its development with offshore aquaculture is the lack of clear regulatory frameworks within existing legislative regimes, and the fact that these may contradict each other. Given that ORE and offshore aquaculture are both developing industries, individual consenting processes are complicated and uncertain, which may compound the challenges associated with the co-location of projects. Additionally, there are concerns about the potential cumulative effects of both ORE and aquaculture industries on the environment. Monitoring environmental effects within pilot and demonstration projects will be necessary to combat and mitigate potential challenges. For the development of co-located ORE and aquaculture projects, the main challenges are the low levels of ORE device commercialization, unknown consequences of the interactions between the two uses, and a lack of knowledge about technical and financial risks.

5.3 Examples around the World

In addition to the general opportunities and challenges for co-location, examples of opportunities and challenges in several countries (Australia, Chile, China, Indonesia, the Philippines, and the United States) were identified and are detailed below. Examples of offshore aquaculture and ORE are the main focus, but because these industries are nascent, opportunities and challenges also include nearshore aquaculture as well as other renewable energies because associated similarities and learnings may be applicable.

Australia

Australia has large ORE resources within reasonable proximity to population centers and potential industry users. For example, Australia's wave energy flux across the 25 m contour of approximately 1,800 TWh/year is the largest of any country in the world, and the tidal range resource of approximately 2,000 TWh/year represents over 20% of the global resource (Hemer et al. 2017). In Australia, the aquaculture sector accounts for 36% of total seafood production (97,406 tonnes of 265,975 tonnes total), of which salmonids are the most valuable species. The Tasmanian salmon industry presents a promising market for co-location with ORE because it accounts for over 98% of salmonid production value (ABARES 2018). While existing at-sea grow-out sites are located primarily within sheltered sites, the current intent suggests that future salmon farming expansion plans will shift operations to more exposed energetic and offshore sites (Duniam and Barnett 2021). Moving production offshore will also help inform the integration of farming multiple species offshore (Carter et al. 2020). A major long-term challenge for offshore salmon aquaculture production will be to successfully resolve the priorities of different stakeholders, to grow multiple species, and to co-locate aquaculture with renewable energy systems (Carter et al. 2020).

To reduce the sectors' reliance on diesel fuel and increase energy efficiency, the BE CRC has proposed offshore developments with integrated systems for Atlantic salmon production that will recycle waste streams and use ORE and/or other types of renewable energy. The BE CRC's Offshore Renewable Energy Systems program aims to advance the technological and commercial readiness of emerging ORE technologies to decarbonize offshore industries, including aquaculture (Penesis and Whittington 2021). Several efforts are ongoing to understand energy demand from Atlantic salmon aquaculture. These include the MoorPower project (see case study in Chapter 4) that will collect data to provide energy estimates from a feed barge operating in the offshore area of Tasmania, and a scoping project that records the energy demand profiles for two different feed and lighting barges that are operational in nearshore environments. The results from these studies will allow the BE CRC to estimate profiles for other key energy loads and successfully estimate the annual energy demand based on operational information obtained from salmon producers in Australia (see Figure 2 in Chapter 3). This research is ongoing, and the BE CRC aims to publish the results of this project in late 2022. Other major projects at the BE CRC include the design, manufacturing, deployment, operation and maintenance, and decommissioning of a scaled M4 (short for "Moored MultiModal Multibody") WEC prototype in Albany, Western Australia, to test and validate the infrastructure and supply chain for emerging ORE markets, including the aquaculture industry in the region.

Chile

Chile is among the top 10 aquaculture exporters and the second largest salmon producer globally (FAO 2020). Currently, Chilean aquaculture includes finfish, shellfish, and algae, and most aquaculture operations are concentrated in the sheltered channels and fjords of the southern regions of Los Lagos, Aysén, and Magallanes. While these operations are currently located within protected environments, there is an increased interest in cultivating salmon in more exposed areas (Chávez et al. 2019). The need for clean energy in the aquaculture sector (including wave and tidal energy) and energy storage solutions such as green hydrogen have been identified and are currently part of the secretarial roadmaps and long-term strategies for Chile (e.g., Alvial et al. 2021). Integrating ORE and aquaculture has been explored within the last decade as a part of these roadmaps and strategies (e.g., Prospectus Consulting 2016).

The potential for ORE in Chile is large (Guerra et al. 2017; Lucero et al. 2017), and its development has been supported by the creation of the Marine Energy Research and Innovation Center in 2015. This center currently operates and monitors a WEC pilot project (OpenSeaLab), alongside the execution of different applied research and innovation projects. One project is currently analyzing the integration of ORE and aquaculture under the local conditions found in Chile. This project includes aspects related to mooring, structural design, hydrodynamic response, seabed mechanics, construction, transport, installation, operation, maintenance, and decommissioning, and is expected to provide a decision matrix for different scenarios by 2023. In the short term, wider knowledge about the challenges and opportunities of ORE and aquaculture co-location is expected, which can in turn act as a driver for applying policies and instruments to support these sectors in the mid-term.

China

As a leader in the global aquaculture industry, China has a growing market and significant potential to move the industry into deeper, offshore waters. China has also been testing the use of ORE for several years throughout the country, mainly targeting islanded areas. Since 2010, China has successively launched a series of wave energy and tidal current energy demonstration projects in Shandong, Zhejiang, Guangdong, and Hainan, and has gradually formed the Guangdong Wanshan Islands Wave Energy Demonstration Zone and Zhejiang Zhoushan Islands Tidal Current Energy Demonstration Zone (IEA-OES 2021; Liu and Bahaj 2021). China's first megawatt-level wave energy demonstration project has begun, and two WECs were constructed and tested at sea (Tethys 2022d). These ORE projects have the potential to be combined with aquaculture operations.

However, the development of co-located offshore aquaculture and ORE projects in China involves some challenges. Offshore ORE projects in China face a much harsher environment than nearshore projects because of the frequent occurrence of typhoons in the China Sea (Jiang et al. 2020; Li et al. 2022). From a policy and regulatory perspective, China has only recently begun to address opportunities for ORE development (Liu 2019). In 2021, ORE was recognized as a key opportunity and thus was included in the *14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2035* (CSET 2021). This helps ensure the development of China's ORE sector at the national policy level. China is also currently investigating tax preferential policies to attract more private enterprises to enter the ocean energy sector and improve their market competitiveness (IEA-IRENA 2021). Additionally, China has provided financial support for powering aquaculture with ORE, which supported the development of a WEC power system for offshore aquaculture that was deployed with the aquaculture platform Penghu (see case study in Chapter 4). This investment in developing aquaculture-specific ORE technologies shows the potential for opportunities in China to advance co-location.

Indonesia

Indonesia is one of the top exporters of farmed seafood in the world, and aquaculture is increasingly being looked upon as a vast, resource-rich opportunity to address food supply and security challenges (Diedrich et al. 2019; Rimmer et al. 2021). In Jakarta, remote northern islands are playing an important role in the growth of aquaculture as an opportunity to mitigate these challenges. The United Nations Habitat program selected Pangang Island, one of these northern islands, as a focus area for the development of an initial "aquaculture village" to farm grouper. This development includes solar PV energy integrated with the floating finfish net cages as an energy source, thereby providing a model for future aquaculture villages to use renewable energy (Hendarti et al. 2018). Indonesia has seen the success of the aquaculture village concept and plans to have a national network of 136 similar villages dedicated to aquaculture by the end of 2022 (Suriyani and Ambari 2022). The use of renewable energy is a key part of these efforts to provide power in remote areas. The aquaculture industry has welcomed the government initiative, although industry proponents indicate the program must be supported by sound environmental planning, particularly avoiding the clearing of mangrove forests and avoiding polluting the surrounding areas through careful use of renewable energy versus fossil fuels and proper waste management.

Indonesia's ORE potential is vast with thermal energy gradient, tidal current, and wave energy amounting to more than 700 GW of ORE resource potential that is spread among numerous sites and areas in the country (Quirapas et al. 2015). In line with Indonesia's various thrusts for achieving a sustainable ocean economy (OECD 2021), ORE and aquaculture are among the marine sectors that the country is looking to develop further.

Philippines

In the Philippines, aquaculture is increasingly demonstrating the ability to help address the challenges of poverty (Irz et al. 2007; Palanca-Tan 2018). With a vast archipelago of more than 7,000 islands, the most suitable areas for aquaculture are often the most remote, off-grid areas. Several islands and coastal areas in the Philippines have various forms of aquaculture operating on a wide range of scales that serve a spectrum of markets (e.g., export, local/domestic products). Although aquaculture and other farming activities have been stunted due to the lack of power available for the "off-grid" island communities, the use of renewable energy in aquaculture in the Philippines has been increasing.

Several programs, projects, and initiatives are positive indicators that the use of sustainable energy in sectors such as aquaculture is being explored as part of a wider sustainable development agenda that looks at the synergy of energy, food, water, environment, and livelihoods in the Philippines. Examples are the Philippines' Department of Energy National Renewable Energy Program studying ocean energy applications; the Philippines Energy Plan 2020 to 2040, which includes the productive use of renewable energy, highlighting agriculture and aquaculture as sectors where sustainable energy should be incorporated (Department of Energy 2020); the European Union-funded "Renewable energy in Tawi-Tawi for seaweeds" project (Padillo 2021); the NAMA Facility-supported "Decarbonization of electricity generation on Philippine Islands - Using tidal stream and solar PV" project (NAMA Facility 2022); and the overall push for blue economy industries (Verdejo 2022).

With an estimated ORE resource potential of 170 GW, which includes thermal energy gradients, tidal current, and wave energy (Quirapas et al. 2015), there is potential for ORE to support aquaculture in the Philippines. However, the development of ORE to support aquaculture in remote areas faces several challenges that will need to be overcome. These include the burden of high capital cost to initiate renewable energy alternatives and to install, maintain, and repair ORE infrastructures. Another challenge is the lack of equipment, support infrastructure, and trained professionals needed for the installation, operation, and maintenance of both ORE and aquaculture systems. Nevertheless, the Philippines presents an important opportunity for ORE growth in support of aquaculture.

United States

In 2018, the value of aquaculture production in the United States represented 21% of the total value of seafood production in the country (NMFS 2021). The total production of marine aquaculture was 44,000 tonnes, which includes the production of species such as Atlantic salmon, clams, mussels, and oysters. Aquaculture production in the United States is low (17th in 2018 worldwide) and between 70 to 85% of the seafood is imported, but there is continued interest in growing the sector in the United States. Reflecting the aquaculture industry trend of moving from nearshore to offshore operations, there has recently been increased support from the United States government for offshore aquaculture, including calls to expand sustainable seafood production, create jobs, and explore opportunities for offshore projects (Executive Order 13921). This also includes efforts by the government to identify study areas for Aquaculture Opportunity Areas to aid in the siting of offshore aquaculture (Morris et al. 2021; Riley et al. 2021). However, consenting processes for both aquaculture and ORE developments still are complex challenges.

The annual potential of United States ORE resources is 2,300 TWh across all 50 states, including the possibility to harness energy from wave, tidal, ocean current, and ocean thermal gradients (Kilcher et al. 2021), and additional potential for ORE across the United States territories. Finding alternative markets for ORE has recently been supported by the US DOE through their "Powering the Blue Economy" initiative, which specifically includes powering offshore aquaculture with ORE (LiVecchi et al. 2019). One example of such efforts includes a preliminary analysis of co-location focused on wave energy and offshore finfish aquaculture. Two United States regions, off the coast of California and Hawaii, were assessed based on relevant environmental, regulatory, and logistical parameters for both aquaculture and wave energy. The preliminary study identified suitable locations for co-location offshore of O'ahu, Hawaii, and Northern California that have both adequate wave resources for wave energy and favorable conditions for aquaculture operations. Other research undertaken under Powering the Blue Economy includes co-locating offshore integrated multi-trophic aquaculture with wave energy, using tidal energy to tumble oysters, and powering kelp processing with tidal energy.

5.4 Summary of Opportunities and Challenges

Because few in situ projects exist, testing the opportunities and challenges identified in this chapter to co-locate ORE and offshore aquaculture is limited. As more initiatives employ ORE for aquaculture and co-located projects increase, additional opportunities and challenges will become apparent. Those described in this chapter are categorized into three main themes: technical and operational processes, regulatory processes (including environmental and social aspects), and economic impact, and are summarized in Table 3.

Table 3. Summary of opportunities and challenges for co-locating ocean renewable energy (ORE) and offshore aquaculture.

Theme	Opportunities	Challenges
Technical and Operational Processes	• Shared operation and maintenance. • Shared systems and equipment (e.g., cables, anchors). • Improved energy security and reliability. • Government funding increasing for research and pilot projects to co-locate.	• Limited energy storage. • Increased safety risks at offshore/high-energy sites. • Low levels of ORE device commercialization. • Unknown interactions between aquaculture and ORE systems.
Regulatory Processes	• Reduced environmental effects (e.g., carbon emissions). • Reduced pollution from oil/fuel spills. • Sustainable and efficient use of marine space. • Potential to develop multi-use platforms. • Low visibility of ORE devices paired with offshore aquaculture. • Reduced conflict/competition for coastal areas by moving offshore.	• Potential cumulative effects. • Potential stakeholder concerns (e.g., environmental effects, conflicts with existing uses, etc.). • Resolve the different priorities of various stakeholders. • Unclear and long licensing procedures. • Need for political/policy support.
Economic Impact	• Cost savings associated with sharing equipment, operations, and technologies. • Cost savings from onsite power generation. • Potential for increased market value of aquaculture products grown using ORE.	• More financial support needed (e.g., funding, investment, etc.). • High cost of offshore equipment. • High upfront capital expenditure.

6. RECOMMENDATIONS

Based on the information presented in the previous chapters, several recommendations to expand the potential for co-location and further understanding of powering offshore aquaculture with ORE have been identified. The recommendations below are not exhaustive, but rather provide initial steps to advance co-location of these novel industries. Based on the categories of opportunities and challenges identified in Chapter 5, the recommendations are combined within these same three themes: technical and operational processes, regulatory processes, and economic impact.

6.1 Technical and Operational Processes

This theme includes any aspect of ORE, aquaculture, or shared processes falling under operational or technical needs of the co-located system and includes but is not limited to daily operations, monitoring, maintenance, safety, and device and system technology. Within these technical and operational processes, two areas stand out for future efforts and research – understanding energy needs more thoroughly and assessing hybrid solutions that can make ORE more viable to pair with offshore aquaculture.

Energy Needs of Aquaculture Operations

More information, including finer-resolution data, about energy demand and the associated energy demand profiles (e.g., daily, monthly, seasonally, for specific stages/processes) for offshore aquaculture operations is needed. The construction and operation of large-scale, semi- or fully autonomous, and/or submersible, offshore aquaculture operations, particularly finfish farming, require high-energy use and will likely increase total energy demands. While the energy demands reported in this report focus mainly on at-sea operations, there is also potential for ORE to provide an alternative to diesel fuel for powering vessels. This potential should be considered as energy data are collected. As more offshore aquaculture operations are developed, gathering data about the associated energy demands is necessary to better identify the potential for ORE to provide power for offshore aquaculture and will allow ORE developers to determine the suitability of their devices within the aquaculture operations.

Assessing the ORE resource (e.g., type of resource available to provide power, seasonality of the resource, etc.) and the energy demands at existing aquaculture facilities will also inform the design and/or selection of devices adapted to available resources. Creating partnerships between aquaculture and ORE developers for pilot project opportunities will advance this effort. Identifying the region and species of interest for co-locating ORE and aquaculture is key to better understanding what types of ORE resource and technology are adapted to the type of aquaculture. As more pilot or demonstration projects are conducted, additional lessons learned from operational setup and providing power for aquaculture can be gained and should be shared within and across these industries.

Hybridization

Hybrid energy solutions (e.g., solar PV and tidal energy, solar PV and wave energy, diesel and wave energy, etc.) could contribute to the development of the ORE and aquaculture sectors. These synergies have the potential to increase the use of ORE technologies for aquaculture operations by offering more reliable and clean ways to supply power than depending on one source of energy. Hybrid solutions may also be necessary to ensure a continuous supply of energy and replace current diesel use. Hybridization can also promote the productive use of renewable energy in the food production sector allowing for more energy solutions that can be paired with aquaculture operations at a variety of locations.

Hybrid barges provide an easy solution for using power generated by waves or tides for offshore aquaculture. Typical feed barges serve as the control center, including providing power, for offshore aquaculture operations. Hybrid barges enable the use of batteries and a power management system where renewable energy sources can be used (AKVA 2020). An important next step for assessing the ability of ORE to power offshore aquaculture operations is exploring the specific designs of ORE devices that can be incorporated with hybrid feed barges. Understanding energy needs and engineering requirements to have the power produced from ORE feed into hybrid barges will bring this closer to reality.

6.2 Regulatory Processes

Focusing on better understanding regulatory needs for co-location is important to help advance opportunities for ORE and offshore aquaculture as regulatory regimes are complex, uncertain, and can be costly. Recommendations under this theme include improvements regarding planning; siting; licensing, consenting (or permitting), and authorization; understanding environmental and social effects; and other aspects. Aiding efficient and effective navigation of regulatory processes will help bolster co-location success.

Environmental and Social Effects

Research on the environmental and social effects of co-locating ORE and offshore aquaculture is needed to promote the synergy of both sectors, to facilitate consenting processes of co-located projects, and to support strategic marine spatial planning. Such assessments will be informed through the collection of baseline environmental and social data and gathering data over time around co-located or multi-use projects. The development of consistent processes and guidance for data collection that are shared and used across both industries will improve the accuracy of the data collected, the ability to compare data between projects to increase learning, and the understanding of the potential environmental and social effects of both offshore aquaculture and ORE. As more activities are sited in the marine environment, this information will also aid studies of cumulative environmental effects.

Once collected, environmental and social data should be accessible to all parties interested in co-located or multi-use projects. Developing online tools and databases can improve the accessibility of such data. For example, the development of integrated assessments (e.g., including ecological, social, and economic aspects) will increase the understanding of multi-sector effects and facilitate planning and siting processes. These efforts can also contribute to stakeholder engagement efforts, allowing for comprehensive planning that accounts for other marine industries, culturally important resources and locations, and potential stakeholder concerns. Turschwell et al. (2020) identified some additional needs and recommendations, including steps to provide support for planning, site selection, and management of cross-sector projects within the blue economy.

Engagement with Aquaculture Stakeholders

To increase the uptake of ORE for aquaculture-relevant applications, there is a need to engage with aquaculture stakeholders (e.g., owners, facility managers, vessel operators, technology providers of moorings/pens/feed barges, policy makers, regulatory agencies, financial organizations, communities, etc.) on a sustainable energy transition. Engaging with stakeholders early in a potential project is necessary to define the opportunities for co-location, which may vary based on the spatial scale of the project and the region targeted. Because co-locating aquaculture and ORE can provide access to a local source of protein, improve food security, and reduce carbon emissions from seafood production, this may be of particular interest for islands and remote coastal areas (OES 2020). Identifying communities where a co-located project would provide benefits and where challenges are limited will be important for the initial pilot and demonstration projects. Transparent and early engagement will help determine such locations, and will also help understand local or regional benefits derived from a project, environmental concerns, possible conflicts with other marine-based industries, and how to mitigate these challenges.

Some suggested pathways for engaging with aquaculture stakeholders may include the following:

- Establishing information, education, and communication campaigns for awareness, training, and consultation/feedback.
- Encouraging partnerships and cross-sector interactions between aquaculture and ORE developers toward decarbonization of the marine food sector.
- Conducting inclusive outreach and engagement with broad groups of stakeholders to develop policies and regulations that enable ORE and aquaculture solutions and responsible development.
- Addressing stakeholder concerns through transparent outreach efforts and identifying benefits or negative impacts and social perceptions of the industries and/or a project.
- Creating tools and toolkits that allow stakeholders to adopt the use of sensors, data collection methods, and energy-efficient interventions in their sustainability journey.
- Developing ORE pilot projects that ramp up the participation and on-boarding of the aquaculture sector (e.g., fish farms as users).
- Providing opportunities for local communities where co-located projects are sited, including training programs and employment.
- Encouraging financial support and allocating funding for the co-development of ORE and offshore aquaculture to advance co-location.

Planning and Licensing

Identifying licensing and planning frameworks in different countries or regions that may foster co-location will identify areas that have fewer barriers and challenges. Such licensing regimes that may benefit co-location or reduce place-based challenges can increase opportunities for both the ORE and aquaculture industries. For instance, assessing existing national or regional marine spatial plans to find those that specifically call for co-location or offer pathways to development can aid industry planning efforts. The development of a roadmap for co-location will help determine a clear pathway toward licensing. This can be done by researchers in collaboration with ORE and aquaculture industry partners. A roadmap can be developed on a broad scale for advancing co-location or within countries or regions to provide opportunities for industries. Such roadmaps could include identifying key stakeholders, regulatory frameworks and policies, markets and supply chains, available financing or investment, development opportunities (such as regional analyses or site assessments), and possible growth scenarios and recommendations.

6.3 Economic Impact

Development of projects for novel industries like ORE and offshore aquaculture often faces economic challenges due to a lack of funding and the use of high-cost technologies, which is likely to be true for co-located projects. Internationally, there is a need for governmental measures supporting co-location. These measures can create the impetus for both industries to engage with one another and can generate better opportunities for siting, planning, and licensing a project. Funding from governments can be directed to states, territories, and local governments for programs that will promote research efforts and the development of pilot co-located projects at the regional or local scale. Government support in making ORE a viable and cost-competitive alternative to diesel or other renewable energies would also greatly aid co-location. It will aid co-location by providing a market for emerging ORE technologies where they can be competitive and reduce costs via market development.

Creating opportunities for offshore aquaculture and ORE and sharing lessons learned will be crucial to ramping up the possibility of offshore aquaculture as a market for ORE. These activities will benefit from the development of international collaboration on projects and research. International and cross-sector collaboration can help identify knowledge gaps, successes, failures, challenges to overcome, and help develop research agendas. Creating international industry forums and research consortiums could be a viable solution to tackling these challenges.

7. CONCLUSION

As the aquaculture industry continues to expand and moves offshore, a new market opportunity opens for ORE. From the technologies to the geographic location, the diversity of energy resources from the ocean makes the ORE industry a viable option to power offshore aquaculture. Co-locating offshore aquaculture and ORE can promote expansion into offshore areas and increase the sustainability of aquaculture operations, encouraging both the growth of the blue economy and the needed decarbonization of the marine food sector.

One of the main constraints to increasing the use of ORE for offshore aquaculture is the lack of information about energy demands from aquaculture. Aquaculture operations are diverse and differ depending on the species farmed and the geographic location. This report provides available data and information about energy needs for a variety of aquaculture operations in several countries. While energy data are limited at this time, the data aid in understanding how energy demands may vary by aquaculture type, farmed species, and/or country. Offshore finfish aquaculture is a likely candidate for co-location because these operations use a large range of systems and equipment, such as for lighting, feeding, refrigeration, domestic activities, and monitoring, that need power. However, there are likely to be opportunities to co-locate ORE and aquaculture operations that require less energy, as shown in the case studies presented. A better estimate of the energy demands for these aquaculture systems across different projects (species- and location-specific) is required to improve understanding of when ORE is best suited and to aid decision-making when selecting the correct ocean resource for providing power. In addition, improving and testing ORE technologies, especially those built to power aquaculture operations, will offer additional opportunities for co-location.

Both ORE and offshore aquaculture are new industries that are developing. While some projects and research studies are starting to consider co-location, exploring the opportunity of offshore aquaculture as a market for ORE remains in its infancy. As more ORE devices are successfully tested and the development of aquaculture, particularly offshore, increased, new applications will be identified and demonstrated. Lessons can be learned from past and current co-located projects and research studies, as well as projects using other renewable energy sources that have been paired with aquaculture, such as solar PV or offshore wind.

This report details the various challenges to and opportunities for co-locating ORE and offshore aquaculture, associated with technical and operational processes, regulatory processes (including environmental effects and social acceptance), and economic impact. Current challenges include a lack of funding, low levels of ORE device commercialization, and unclear licensing procedures. The ORE industry continues to tackle challenges associated with device commercialization, aided by international test sites and continued research. Funding is also becoming more available as countries are investing in the blue economy and multi-use planning and are targeting renewable energy goals. Co-location offers great opportunities for both industries such as cost savings, shared maintenance and operations systems, and sustainable and efficient use of marine space. Many pilot and demonstration co-location projects are planned and additional research into co-location is being conducted. As new projects and research are carried out, challenges are likely to be overcome and additional opportunities are likely to be identified.

Based on available data, lessons learned from case studies, and findings detailed in this report, recommendations to aid synergies between ORE and offshore aquaculture and advance co-location are presented. These recommendations are grouped into three main areas that require further understanding or provide opportunities for advancement: technical and operational processes, regulatory processes, and economic impact. The needs identified are provided for ORE and aquaculture developers, stakeholders, government agencies, and regulators to understand the existing and future opportunities derived from combining these two industries and to help alleviate potential concerns. These recommendations will help expand the potential for co-location and further the understanding of powering offshore aquaculture with ORE. Although offshore aquaculture and ORE are nascent industries, there is much potential for advancement to help tackle larger problems of feeding the growing population, reducing carbon emissions, and contributing to a sustainable blue economy.

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OFFSHORE AQUACULTURE: A MARKET FOR OCEAN RENEWABLE ENERGY

APPENDIX

Information on aquaculture operations, locations, energy demand, suitability for ocean renewable energy, and regulatory requirements was provided by aquaculture experts in several key nations. These nations are mainly members of Ocean Energy Systems, large aquaculture producing nations, or have interest in expanding aquaculture offshore. The tables below describe the information gathered per country within Asia, Europe, North America, South America, and Oceania.

Asia

China

Table 1. Information on aquaculture practices in China.

Species	Practice type (net pen, rack, etc.)	Location	Conditions of operation	Expansion plans for offshore operations	Energy requirements	Suitability for ocean renewable energy	Regulatory requirements	Other relevant market requirements (e.g., food safety criteria, sustainability, etc.)
Finfish, shellfish, crusta-cean, seaweed, etc.	Sea-pen, rack, artificial reefs, etc.	Nearshore, offshore	Unknown	Floating fish farm, aquacul-ture net cage	Wave energy[1], solar energy, diesel generator	Very suitable	Fisheries legislation, marine regulations	Leisure fishery, food safety criteria, sustainability, etc.

1 http://english.giec.cas.cn/ns/rp/201908/t20190809_213996.html

Japan

Table 2. Information on aquaculture practices in Japan.

Species	Practice type (net pen, rack, etc.)	Location	Expansion plans for offshore operations	Energy requirements	Suitability for ocean renewable energy	Other relevant market requirements (e.g., food safety criteria, sustainability, etc.)	Annual production[2]
Freshwater fishes (carps, barbels, others) fiadromous fishes (river eels, salmons, trouts, smelts)	Ponds	Inland, freshwater	In 2021 Fisheries Agency Japan published *New Plan*	Not clear	Not clear	Recently, the demand for food safety criteria and sustainability is increasing in Japan	31,329 tonnes
Marine finfish – salmons, flounders, halibuts, soles, others)	Net pens	Marine locations	Same as above	Not clear	Not clear		247,100 tonnes
Algae – brown and red seaweeds, and other aquatic plants		Marine locations	Same as above	Not clear	Not clear		345,500 tonnes
Crustaceans – shrimp, prawns		Brackish water	Same as above	Not clear	Not clear		1,400 tonnes
Other species – clams, oysters, scallops, others	Hanging culture	Marine locations	Same as above	Not clear	Not clear		305,500 tonnes

2 https://www.fao.org/fishery/en/statistics

Philippines

Table 3. Information on aquaculture practices in the Philippines from the OceanPixel Database of 2020 Philippines production.

Species	Practice type (sea-pen, rack, artificial reef, etc.)	Location	Conditions of operation	Energy requirements	Suitability for ocean renewable energy	Annual production
Finfish (includes milkfish, tilapia, grouper, signed, carp, catfish, gourami, mudfish)	National all types; rural settings – traditional methods. Brackish water and freshwater fishponds; brackish, freshwater, and marine pens and cages; small farm reservoirs or rice fish farms	Fresh water and marine production; brackish operations usually near marine coastal areas or river mouths; no offshore	Calm waters	Limited energy needs	Low energy demands	717,701 tonnes
Shellfish (includes oyster, mussel)	National all types; rural settings – traditional methods	Nearshore marine and brackish water	Calm waters	Limited energy needs	Low energy demands	72,261 tonnes
Crustaceans (includes tiger prawn, mud crab, endeavor prawn, white shrimp, freshwater prawn, spiny lobster)	National all types; rural settings – traditional methods. Brackish water fishponds, marine pens or cages	Nearshore marine and brackish water (usually near marine coastal areas or river mouths)	Calm waters	Limited energy needs	Low energy demands	64,291 tonnes
Seaweed	National all types; rural settings – traditional methods	Nearshore marine and brackish water	Calm waters	Limited energy needs	Low energy demands	1,468,653 tonnes

Singapore

Table 4. Information on aquaculture practices in Singapore.[3, 4, 5]

Species	Practice type (sea-pen, rack, artificial reef, etc.)	Location	Expansion plans for offshore operations	Energy requirements	Suitability for ocean renewable energy	Regulatory requirements	Other relevant market requirements (e.g., food safety criteria, sustainability, etc.)
Finfish (includes milkfish, mullet, tilapia, barramundi, grouper, snapper, pompano, threadfin, silver grunter, pomfret, marble goby, snakehead, perch, salmon)	Sea-pen, recirculating, rack, open pond, closed tanks, vertical farms	Nearshore (West Johor Strait, East Johor); onshore (Lim Chu Kang, Murai, Pulau Semakau); offshore (Singapore Straits)	Automation, genetic improvement, disease prevention	Aeration, pumping, wastewater treatment, instrumentation	Yes (solar photovoltaic)	SFA License, Temporary Occupation License (starting 2023)	Quality assurance, sustainability badges
Crustacean (includes spiny lobster, shrimp, prawn, crab)	Sea-pen, recirculating, rack	Nearshore, onshore	Automation	Aeration, pumping	Yes (solar PV)	SFA License, Temporary Occupation License (starting 2023)	Quality assurance, sustainability badges
Shellfish (mussel)	Sea-pen	Nearshore	Automation	Aeration	Yes (solar PV)	SFA License, Temporary Occupation License (starting 2023)	Quality assurance, sustainability badges

3 World Aquaculture Society (2020). The Singapore Aquaculture Industry — Contributing to Singapore's Food Security. https://www.was.org/articles/The-Singapore-Aquaculture-Industry-Contributing-to-Singapores-Food-Security.aspx#.YkUMXzURW3A
4 Singapore Food Agency (2022). The Singapore Aquaculture Plan. https://www.ourfoodfuture.gov.sg/uplifting-aquaculture-industry/sg-aquaculture-plan
5 Shen Y., Ma K., & Yue G.H. (2021). Status, challenges and trends of aquaculture in Singapore. Aquaculture 533, 736210. https://doi.org/10.1016/j.aquaculture.2020.736210

Europe

Information provided for each country in the European Union (Belgium, France, Spain) was supplemented by information from the European Union Aquaculture Sector – Economic Report 2020 (STECF 20-12).[6]

Belgium

Table 5. Information on aquaculture practices in Belgium provided by the Belgium Blue Energy Cluster on aquaculture farms and potential pilot projects.

Species	**Practice type** (net pen, rack, etc.)	**Location**	**Conditions of operation**	**Size of operation**	**Energy requirements**	**Suitability for ocean renewable energy**	**Regulatory requirements**	**Other relevant market requirements** (e.g., food safety criteria, sustainability, etc.)
Oyster[7]	Long-line system with cages	Inland – in harbor; North Sea	High turbidity, no waves, high nutrients, brackish water	8 ha farm	N/A	None	Sanitary requirements	Food safety
Oyster	Oyster tables and cages (bottom)	Windpark (30 km offshore); Belgian coast – UNITED project[8]	Less nutrients, high waves and currents, strong wind, 30 m depth	1 ha pilot project	N/A	To be determined (TBD)	Signal boys - security	
Oyster, mussel, seaweed, passive fisheries[9]	Long-line with droppers	Nearshore (5 km from shore); North Sea	High nutrient, currents and waves, 10 m depth	1 ha pilot project	NA	TBD	Signal boys - security	
Mussel (seaweed, oyster)	Long-line with droppers	Nearshore (5 km from shore); North Sea	High nutrient, currents and waves, 10 m depth	7 ha (2 steps)	NA (remote monitoring & data transfer – warning systems)	TBD (solar, wave energy)	Environmental impact, signal boys - security	Food safety
Seaweed	2D textile substrates (AtSeaNova)	Windpark (30 km offshore) Wier & Wind[10]	Less nutrients, high waves, currents, strong wind, 30 m depth	1 ha pilot project	NA	TBD	Signal boys - security	

6 https://stecf.jrc.ec.europa.eu/reports/economic/-/asset_publisher/d7Ie/document/id/2871698
7 http://www.aquacultuur.be/
8 https://www.h2020united.eu/pilots/2-uncategorised/42-offshore-wind-and-flat-oyster-aquaculture-restoration-in-belgium
9 https://www.blauwecluster.be/project/symapa-synergy-between-mariculture-passive-fisheries
10 https://www.grensregio.eu/projecten/wier-wind

England

Table 6. Information on aquaculture practices in England.

Species	**Practice type** (sea-pen, rack, artificial reef, etc.)	Location	Expansion plans for offshore operations	Energy requirements	Suitability for ocean renewable energy	Regulatory requirements	**Other relevant market requirements** (e.g., food safety criteria, sustainability, etc.)	Annual production
Finfish (salmon, trout, bass, bream, flatfish, etc.)	Finfish open net pens & submerged cages. Pump ashore flow through finfish farms, Aquaponics Farm, Integrated Multi-Trophic Aquaculture (IMTA), recirculating aquaculture system (RAS)	Marine, land based, freshwater	Strategic objectives: Tenfold growth and diversification of aquaculture in England over the next 20 years, with farmed production contributing at least 15% of overall seafood consumption by 2040. Encourage the development of low trophic species and the use of integrated multi-trophic aquaculture to contribute to England's netcarbon zero ambitions.[11]	Boats, barge, lights, feeding, RAS/ land-based facility	Yes, wave	Planning Permission (local authorities), marine license (MMO), EIA/ HRA (CEFAS), Authorization to operate an APB, authorization to import livestock (FHI), permitting farming of alien species (FHI), Abstraction & Discharge Licenses. Fish supplier permitting (EA), Seabed/Foreshore Lease (CE), Documentation/ training of Seafarers, Seafarer Safety and Health, Counter Pollution, Environmental Policy, Search and Rescue, Survey and Inspection, Ship Standards, Enforcement, Receiver of Wreck (MCA), etc.[12]	Strategic principles: Aquaculture production should be environmentally, economically and socially sustainable. Effective co-existence of aquaculture with other maritime activities, including wild capture fisheries, is key. A co-management, partnering approach is developed between regulators, the industry and other stakeholders.	6,456 tonnes (2014)
Seaweed and kelp (though does not seem to be an established industry)	Marine and land-based	Integrated Multi-Trophic Aquaculture (IMTA), Macro-algae Culture	Same as above	Boat, RAS/ land-based facility	Yes, wave	Same as above	Same as above	

11 https://www.seafish.org/about-us/working-locally-in-the-uk/working-with-the-seafood-industry-in-england/seafood-2040/english-aquaculture-strategy-from-seafood-2040/
12 https://www.seafish.org/document?id=8d3f8157-7ad1-4b0b-a1d4-3e92bda65066

Shellfish (mussels, scallops, oysters, clams, lobster)	On-bottom (trestles, or ground cultured), off-bottom (long line or raft), Crustacean Cage Culture, Integrated Multi-Trophic Aquaculture (IMTA), RAS	Marine and land based	Same as above	Boat, feeding, RAS/land-based facility, barge	Tidal or wave may be possible	Same as above	Same as above	2,456 tonnes (2014)

France

Table 7. Information on aquaculture practices in France from the Fisheries and Aquaculture Sector in France 2020 report.[13]

Species	**Practice type** (sea-pen, rack, artificial reef, etc.)	**Location**	**Expansion plans for offshore operations**	**Energy requirements**	**Suitability for ocean renewable energy**	**Other relevant market requirements** (e.g., food safety criteria, sustainability, etc.)	**Annual production**
Oyster	Rafts, long lines, bottom harvest		No plans to move offshore	Dredges, beam trawl, boats, equipment	Yes, especially oyster farming suitable for river current energy	European Green Deal, Farm to Fork Strategy[14], European Maritime, Fisheries, and Aquaculture Fund (EMFAF)	81,000 tonnes
Mussel	Rafts, long lines, bottom harvest		No plans to move offshore	Dredges, beam trawl, boats, equipment	Yes	Same as for oysters, plus Traditional Specificity Guaranteed (TSG)	51,000 tonnes
Other bivalves	Rafts, long lines, bottom harvest		No plans to move offshore	Dredges, beam trawl, boats, equipment	Yes	Same as for oysters	3,000 tonnes
Trout and salmon	Net pens, lakes (trout)	Trout – freshwater	No plans to move offshore	Boats, equipment, enclosure maintenance, hatchery operations	Depends on proximity	Same as for oysters	36,000 tonnes
Carp and other freshwater fish	Lakes, net pens	freshwater	No plans to move offshore	Boats, equipment, enclosure maintenance, hatchery operations	Depends on proximity	Same as for oysters	8,100 tonnes
Seabass, seabream, and other marine finfish			No plans to move offshore			Same as for oysters	3,900 tonnes
Macroalgae	Longlines, rafts, tanks (land based)	Offshore, nearshore, land based		Boats, equipment for harvest, seeding facilities	Yes	Same as for oysters	
Microalgae and *Spirulina spp.*	Tanks	Offshore, nearshore, land based		Facilities operation, water pumps	Depends on proximity	Same as for oysters	

13 https://www.franceagrimer.fr/fam/content/download/65441/document/CC%20p%C3%AAche%20aqua%20ANG%20web.pdf?version=1
14 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:236:FIN

Ireland

Table 8. Information on aquaculture practices in Ireland is from the National Seafood Survey: Aquaculture Report 2019[15]. Additional information can be found in the Business of Seafood 2020: A Snapshot of Ireland's Seafood Sector.[16]

Species	Practice type (net pen, rack, etc.)	Location	Expansion plans for offshore operations	Energy requirements	Suitability for ocean renewable energy	Regulatory requirements	Other relevant market requirements (e.g., food safety criteria, sustainability, etc.)	Annual production
Atlantic salmon (*Salmo salar*)	Net pens, sea cages	Near-shore, typically in bays or in the lee of an island	Currently no plans to move offshore due to a licensing backlog.	Boats, diving, feeding, treatments (energy for freshwater treatments – pumps), and grading	Yes, for offshore, nearshore activities. Site dependent.	Marine aquaculture operators must hold an aquaculture license and a foreshore license, as issued by the Department of Agriculture Food and the Marine.[17] Finfish (salmon) sites must not exceed their maximum tonnage, undertake environmental monitoring, notify the authorities on health status of the stock, keep full records on chemicals and therapeutics, keep the culture structures (cages etc.) in a proper state of repair and condition and demarcate the area with suitable navigation aids.	A number of schemes are used across the marine aquaculture sector: Aquaculture Stewardship Council, Naturland, BioSuisse, Irish Organic Association (compliant with EC Council Regulation No. 834/2007[18]), Certified Quality Aquaculture (CQA) Programme[19]. Global Trust, Carbon Trust, Bord Bia, Origin Green[20], ECOPACT, Bord Iascaigh Mharas – certified quality aquaculture programme, Global Salmon Initiative (GSI), Global GAP, BRC Global Food standard, Agriculture Biologique, Bio-Siegel, Kosher certified (KLBD)	14,000 tonnes

15 https://bim.ie/wp-content/uploads/2021/02/BIM-National-Seafood-Survey-Aquaculture-Report-2019.pdf
16 https://bim.ie/wp-content/uploads/2021/03/BIM-The-Business-of-Seafood-2020.pdf
17 https://www.gov.ie/en/publication/fcd20-aquaculture-foreshore-management/#aquaculture-licensing
18 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32007R0834
19 https://bim.ie/aquaculture/sustainability-and-certification/certified-quality-aquaculture-cqa-programme/
20 https://bim.ie/aquaculture/sustainability-and-certification/irish-seafood-business-and-origin-green/

Pacific oyster (*Crassostrea gigas*)	Trestles and longlines	Intertidal regions	Same as above	Machinery, grading, hatcheries	Same as above	Mussel, oyster and seaweed sites must also have an aquaculture and a foreshore license and comply with similar environmental and planning requirements. [21]	Similar to above	10,000 tonnes
Blue mussel (*Mytilus edulis*)	Bottom and rope	Deeper coastal waters	Same as above	Boast, diving, machinery, grading	Same as above	Same as above	Similar to above Marine Stewardship Council for bottom and rope grown[22,23]	Rope – 9,000 tonnes Bottom – 6,000 tonnes
Seaweeds (*Palmaria palmata* and *Laminaria digitata*)	Longlines and ropes	Nearshore	Same as above	Boats, divers, grading, machinery	Same as above	Same as above	Similar to above	40 tonnes

Northern Ireland

Table 9. Information on aquaculture practices in Northern Ireland.

Species	**Practice type** (sea-pen, rack, artificial reef, etc.)	Suitability for ocean renewable energy	Regulatory requirement	**Other relevant market requirements** (e.g., food safety criteria, sustainability, etc.)	Annual production
Finfish (mainly salmon (*Salmo salar*), rainbow trout (*Oncorhyncus mykiss*), brown trout (*Salmo trutta*).	Land based and coastal	Limited	Under the Fisheries Act (Northern Ireland) 1966, as amended, DAERA Marine and Fisheries Division is responsible for the licensing of fish farms and shellfish farms. This includes the granting of fish culture licenses, shellfish fishery licenses and marine fish fishery licenses.[24] The Division is also responsible for the registration and approval of aquaculture establishments under Regulation (EU) 2016/429 (The Animal Health Law).	RSPCA assured, Label Rouge accreditation, Organic - Soil Association, Aquaculture Stewardship Council, Code of Good Practice (CoGP), Global GAP	750 tonnes (2014) In 2018, the two main finfish species in produced just over 3,000 tonnes
Shellfish (mainly mussels (*Mytilus edulis*) and Pacific Oysters (*Magallana gigas*), and small quantity of Native oysters (*Ostrea edulis*))	Coastal	Wave or tide may be possible	Same as above	Same as above	3,238 tonnes (2014) In 2019 the total tonnage of shellfish (blue mussel, pacific oyster) was 1,797 tonnes

21 https://www.gov.ie/en/publication/fcd20-aquaculture-foreshore-management/#aquaculture-licensing
22 https://fisheries.msc.org/en/fisheries/ireland-rope-grown-mussel/
23 https://fisheries.msc.org/en/fisheries/ireland-bottom-grown-mussel/@@view
24 https://www.gov.uk/aquaculture-licence-northern-ireland

Norway

Table 10. Information on aquaculture practices in Norway.

Species	Practice type (sea-pen, rack, artificial reef, etc.)	Location	Expansion plans for offshore operations	Energy require-ments	Suitability for ocean renewable energy	Regulatory requirement	Other relevant market requirements (e.g., food safety criteria, sustainability, etc.)	Annual production
Finfish (mainly salmon and rainbow, but also cod and halibut)	Sea pens, land based, recirculating aquaculture system (RAS), offshore (niche segment in Norway)	Near-shore/ fjords	Already operations in place; government continuing to facilitate offshore aquaculture[25]	Boats, barge, lights, feeding, processing, packaging, smolt production, grow-out, feed and transport	Yes, wave possible; Norwegian firm developing a floating solar project for offshore deployment to power small remote islands, utility grids, oil and gas operations and fish farms[26]	Each farm must have a license to operate and be located in open seas or fjord in an area that protects the environment and native stocks Permits are required for the farming of broodstock and young fish, but the permits do not limit the quantity. Each commercial permit for grow-out gives the right to have up to a certain amount (biomass) of living fish in the sea (780 tonnes per permit, but 945 tonnes in Troms and Finnmark). Under Norway's traffic light system, companies that meet certain sea lice thresholds are allowed to produce more fish.[27]	Many requirements of license to avoid environmental effects and with strict monitoring[28, 29] Many Norwegian fish farming companies are certified under one or more standards[30] Norwegian Accreditation serves as public accreditation body. Others include Global G.A.P Aquaculture standard - Aquaculture Stewardship Council (ASC) - Certifications for production of organic salmon (e.g., Debio[31])	2018-2019[32]: 1,364,044 tonnes salmon; 83,489 tonnes rainbow trout; 519 tonnes char; 1525 tonnes halibut 2020[33]: almost 1.5 million tonnes of farmed fish produced

25 https://svw.no/en/insights/an-introduction-to-the-governments-new-aquaculture-strategy
26 https://www.aquaculturealliance.org/advocate/renewable-energy-could-transform-offshore-aquaculture-but-what-about/
27 https://www.forskningsradet.no/siteassets/publikasjoner/2021/an-evaluation-of-the-scientific-basis-of-the-traffic-light-system-for-norwegian-salmonid-aquaculture.pdf
28 https://seafoodfromnorway.co.uk/stories-from-norway/the-gift-keeps-on-giving/innovating-a-new-industry---aquaculture/
29 https://www.barentswatch.no/havbruk/areal-use
30 https://www.barentswatch.no/havbruk/certifications
31 https://debio.no/akvakultur/
32 https://www.ssb.no/en/fiskeoppdrett/
33 https://www.regjeringen.no/no/dokumenter/havbruksstrategien-et-hav-av-muligheter/id2864482/?ch=3

Shellfish (scallop, and blue mussels)	Sea pens, land based, RAS	Near-shore/fjords	Government continuing to facilitate offshore aquaculture	Boats, barge, lights, feeding	Tidal and wave possible		Label Rouge accreditation, Aquaculture Stewardship Council	2018-2019: 2,164 tonnes of shellfish
Kelp/seaweed (sugar kelp (*Saccharina latissima*), winged kelp (*Alaria esculenta*), red and purple laver (*Porphyra spp.*) and the red sea lettuce (*Palmaria palmata*))	Macro-algae culture; previous research projects involving monoculture polyculture or in fjord restoration	Near-shore/fjords	Government continuing to facilitate offshore aquaculture			Algae is a new priority in aquaculture. The first commercial cultivation permits were awarded in 2014[34] Regulatory bodies involved in aquaculture licensing are the Norwegian Food safety Authority, the Ministry of Health and Care Services, the Ministry of Agriculture and Food and the Norwegian Agricultural Authority.	Harvest of seaweed is restricted in bird reserves, where seaweed harvesting can be totally banned, or partly allowed outside of the bird breeding season. Where areas are environmentally protected, it has to be specified in the regulations related to the specific area if aquaculture activity is allowed or not.[35]	2020 (preliminary figures)[36]: 96 tonnes sugar kelp; 88 tonnes winged kelp
Crustacean (European lobster)	Sea ranching	Near-shore/fjords	Government continuing to facilitate offshore aquaculture	Boats				

34 https://www.fiskeridir.no/English/Aquaculture/Statistics/Algae

35 https://docplayer.net/21084209-The-norwegian-seaweed-industry-work-package-1-2.html

36 https://www.fiskeridir.no/English/Aquaculture/Statistics/Booklets/_/attachment/download/c83db45d-6da9-4b35-8c44-da03fea5424f:5884ad22b5b148dfa175d2ac552e3220679661e0/nokkeltall-havbruk-2020-eng.pdf

Spain

Table 11. Information on aquaculture practices in Spain.

Species	Practice type (net pen, rack, etc.)	Location	Expansion plans for offshore operations	Energy requirements	Suitability for ocean renewable energy	Other relevant market requirements (e.g., food safety criteria, sustainability, etc.)	Annual production[37]
Sea bream (*Sparus aurata*)	Sea pen	General nearshore	Yes	Boats, equipment, enclosure maintenance, hatchery operations	Yes	European Green Deal, Farm to Fork Strategy[38], European Maritime, Fisheries, and Aquaculture Fund (EMFAF)	13,521 tonnes
Sea bass (*Dicentrarchus labrax*),	Sea pen	General nearshore	Yes	Boats, equipment, enclosure maintenance, hatchery operations	Yes	Same as above	27,335 tonnes
Corvina (*Argyrosomus regius*)	Sea pen	General nearshore	Yes			Same as above	3,650 tonnes
Bluefin tuna (*Thunnus thynnus*)	Sea ranching and sea pen – trapping, on-growing and enhancing in sea pens	General nearshore	Yes	Boats, equipment, enclosure maintenance, hatchery operations	Yes	Same as above	7,575 tonnes
Oysters (*Crassostrea gigas, Ostrea edulis*)	Racks, baskets	General nearshore and intertidal	No*	Dredges, beam trawl, boats, equipment	Yes		Crassostrea gigas – 1,425 tonnes Ostrea edulis – 394 tonnes
Mussels (*Mytilus galloprovincialis*)	Longline, raft	General nearshore	Yes	Dredges, beam trawl, boats, equipment	Yes	Same as above, plus Traditional Specificity Guaranteed (TSG)	245,655 tonnes

Note that, some commercially important marine species, such as turbot, sole and abalones have not been considered in this table as they are produced in inland facilities (not at sea). Others such as clams, have not considered either as they are cultured buried in estuaries. Oysters can be produced using several techniques, intertidal production in on growing plots, or in vertical cultivation from platforms using hanging baskets.

Seaweed species are not included in the table, as their annual production is under 10 tonnes, being the sea lettuce (*Ulva lactuca*) the most produced seaweed species, production reaching 4.28 tonnes in 2019. Although there is not clear evidence of the aquaculture technique used for production.

*In the Basque Country, Matxitxako Moluskoak SL, local aquaculture company, is interested in the production of oyster in offshore longlines as new species for the diversification of the aquaculture sector. Although there are not overall expansion plans for oyster culture.

37 https://apromar.es/wp-content/uploads/2021/12/Aquaculture-in-Spain-2020.pdf
38 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:236:FIN

Scotland

Table 12. Information on aquaculture practices in Scotland.

Species	**Practice type** (sea-pen, rack, artificial reef, etc.)	Location	Expansion plans for offshore operations	Energy requirements	Suitability for ocean renewable energy	Regulatory requirements	**Other relevant market requirements** (e.g., food safety criteria, sustainability, etc.)	Annual production[39]
Atlantic salmon	Sea pen, freshwater tanks for hatchery, recirculating aquaculture system (RAS) limited	General nearshore. The marine farms where fish are grown are situated on the West and North Coasts of the Scottish mainland and in the Western Isles, Orkney and Shetland. They are normally positioned in sea lochs and inlets where some shelter is provided from the worst of the weather.	Plans to increase aquaculture, including marine finish, production sustainably.[40] Industry looking to expand to offshore[41]	Boats, barge, lights, feeding. Salmon hatchery:433,182 kWh per year, salmon freshwater loch cages: 74,781 kWh per year, salmon marine sites: 33,070 kWh per year+ around 229, 500 kWh / year2, salmon processing facilities 1,964,705 kWh per year[42]	Yes, wave possible	Town and Country Planning (Scotland) Act 1997, Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017, Water Environment (Controlled Activities) (Scotland) Regulations 2011 (SEPA), Marine (Scotland) Act 2010, Crown Estate Act 1961, Conservation (Natural Habitats, &c.) Regulations 1994, Aquatic Animal Health (Scotland) Regulations 2009, Protection of the Marine Environment, Discharges from Marine Pen Fish Farms: A Strengthened Regulatory Framework (SEPA), National policy: Scotland's Third National Planning Framework (NPF3), Scottish Planning Policy, National Marine Plan, Regional Policy: Local Development Plans and strategies	RSPCA assured, Label Rouge accreditation, Organic - Soil Association, Aquaculture Stewardship Council, Code of Good Practice (CoGP), Global GAP	203,881 tonnes in 2019

39 https://www.gov.scot/publications/scottish-fish-farm-production-survey-2019/documents/
40 http://aquaculture.scotland.gov.uk/our_aquaculture/our_aquaculture.aspx
41 https://thefishsite.com/articles/scotland-set-for-first-open-ocean-farm
42 SARF (Scottish Aquaculture Research Forum). 2014. Renewable power generation on aquaculture sites. Scottish Aquaculture Research Forum. November 2013. 498 pp.

Rainbow trout	Sea pen, freshwater tanks for hatchery, RAS limited	Same as above	Plans to increase marine finish production sustainably	Boats, barge, lights, feeding	Yes, wave possible	Same as above	Same as above	7,405 tonnes in 2019
Other species – brown/ sea trout, halibut, lumpsuck-er, several species of wrasse	Sea pen, RAS limited	Same as above	Plans to increase marine finish production sustainably	Boats, barge, lights, feeding	Yes, wave possible	Same as above	Same as above	41 tonnes, excluding halibut
Seaweed, kelp		General nearshore				Same as above		Mussels – 6,699 tonnes Pacific oyster – 369 tonnes Native oyster – 8 tonnes Scallop – 3 t Queen scallop – 1 tonne
Shellfish – blue mussel, pacific oyter, native (European) oyster, scallop, queen scallop, etc.	Mussels on vertical single ropes or fabric, suspended in the water from heavy horizontal ropes and flo-tation buoys arranged in long lines normally parallel to the shoreline. Scallops can be grown in a similar fash-ion, hanging from lines or grown in small sus-pended net enclosures known as lan-terns. Oysters are normally grown in bags made from heavy plastic mesh, either lying directly on the shore or set up on platforms known as trestles.	General near shore. Farming typically takes place in sea lochs and voes on the West Coast of the Scot-tish Main-land, in the Western Isles and Shetland, with the indented irregular coastline of Scotland offering many ideal sites for shellfish produc-tion.	Plans to increase shellfish production	Oyster farm-ing; 716 kWh per tonne Boats, barge	Tidal/wave may be possible[43]	Same as above	Same as finfish	

43 https://www.offshore-energy.biz/guinard-energies-to-power-french-oyster-farm-with-tidal-turbine/?utm_source=marineenergy&utm_medium=email&utm_campaign=newsletter_2021-08-13

Wales

Table 13. Information on aquaculture practices in Wales.

Species	**Practice type** (sea-pen, rack, artificial reef, etc.)	**Location**	**Energy requirements**	**Suitability for ocean renewable energy**	**Regulatory requirements**	**Other relevant market requirements** (e.g., food safety criteria, sustainability, etc.)	**Annual production**
Finfish (salmon, trout, bass, bream, flatfish, etc.)	Net pens and submerged cages, Integrated Multi-Trophic Aquaculture (IMTA), pump ashore flow through finfish farms, recirculating aquaculture system (RAS), flow through and static water farms, aquaponics farms	Freshwater, marine, land based	Boats, barge, lights, feeding	Yes, wave possible	Planning Permission and Environmental Health (local authorities). Marine License, Planning permission advice and protected area advice, Abstraction & Discharge Permits, Licenses freshwater fish culture and introductions Manage Regulatory Orders (NRW). Identification of preferred areas for aquaculture, Authorization to operate an APB, Permitting farming of alien species, Inspections on behalf of VMD and APHA Habitats Risk Assessment (HRA) (FHI). Environmental Impact Assessment (EIA), Habitats Risk Assessment (HRA) (CEFAS). Seabed/ Foreshore Lease (CE and SE), safety of navigation (markers).[44]	RSPCA assured, Label Rouge accreditation, Organic - Soil Association, Aquaculture Stewardship Council, Code of Good Practice (CoGP), Global GAP	497 tonnes (2014)
Shellfish (blue mussel, Pacific oyster, native oyster, mussels, scallops, oysters, clams, abalone)	longline, trestle culture, on-bottom (trestles or ground cultured), off-bottom (longline or raft), IMTA, RAS, Aquaponics Farm	Marine, inshore locations, freshwater, land based	Boats, barge	Tidal and wave may be possible	Same as above including classification of safe areas for shellfish aquaculture and biotoxin monitoring, Approval of purification plants for shellfish (FSA), Shellfish Waters management & Consultee for FHI APB licensing, WFD shellfish waters designation (WG).	Same as above	7,945 tonnes (2014; includes crustaceans)
Kelp/seaweed	Macro-algae culture, IMTA	Marine, land based	Boats				

44 https://businesswales.gov.wales/marineandfisheries/sites/marineandfisheries/files/documents/Aquaculture%20Regulators%20in%20Wales.pdf

Crustaceans (freshwater crayfish, lob-sters)	Crustacean cage culture, IMTA	Marine, inshore locations, freshwater, land based	Boats				

North America

Canada

Table 14. Information on aquaculture practices in Canada from Fisheries and Oceans Canada 2019 Aquaculture production values[45] and the State of Farmed Seafood in Canada 2020 report.[46]

Species	**Practice type** (net pen, rack, etc.)	**Location**	**Conditions of operation**	**Energy requirements**	**Suitability for ocean renewable energy**	**Regulatory requirements**	**Other relevant market requirements** (e.g., food safety criteria, sustainability, etc.)	**Annual production**
Trout (steelhead, rainbow, artic, char, brook)	Freshwater, new pens, lakes, closed systems, tanks	New-found-land, Labrador, Prince Edward Island, Quebec, Ontario, Manitoba, Saskatch-ewan, Alberta, British Columbia, Yukon	Inland (lakes, potholes, river systems)	Boats, equipment, enclosure maintenance, hatchery operations	Depending on proximity	Fisheries and Oceans Canada	Health of Animals Act, Food and Drugs Act, Species at risk Act	8,618 tonnes (2019)
Salmon (Atlantic, etc.)	Recirculating aquaculture system, hybrid offshore and inland systems, floating closed containment systems	New-found-land, Labrador, Nova Sco-tia, New Bruns-wick, British Columbia	Both inland and offshore	Boats, equipment, enclosure maintenance, hatchery operations	Yes	Fisheries and Oceans Canada	Health of Animals Act, Food and Drugs Act, Species at risk Act	117,934 tonnes (2019)
Other finfish (e.g., tilapia, Grass carp)	Freshwater, net pens, lakes, closed systems, tanks	Alberta	Inland (lakes, potholes, river systems)	Boats, equipment, enclosure maintenance, hatchery operations	Depending on proximity	Fisheries and Oceans Canada	Health of Animals Act, Food and Drugs Act, Species at risk Act	1,814 tonnes (2019)

45 https://www.dfo-mpo.gc.ca/stats/aqua/aqua19-eng.htm
46 https://waves-vagues.dfo-mpo.gc.ca/Library/40864492.pdf

Clams	Rafts, suspended lines, netting, hatcheries for seed	Newfoundland, Labrador, Prince Edward Island, Nova Scotia, Quebec, British Columbia	Onshore, nearshore	Boats, harvesting equipment, water quality monitoring, seeding	Yes	Fisheries and Oceans Canada	Health of Animals Act, Food and Drugs Act, Species at risk Act	1,814 tonnes (2019)
Oysters	Rafts, suspended lines, netting, hatcheries for seed	Prince Edward Island, Nova Scotia, New Brunswick, Quebec, British Columbia	Onshore, nearshore	Boats, harvesting equipment, water quality monitoring, seeding	Yes	Fisheries and Oceans Canada	Health of Animals Act, Food and Drugs Act, Species at risk Act	14,514 tonnes (2019)
Mussels (blue mussel)	Rafts, suspended lines, netting, hatcheries for seed	Newfoundland, Labrador, Prince Edward Island, Nova Scotia, Quebec, British Columbia	Onshore, nearshore	Boats, harvesting equipment, water quality monitoring, seeding	Yes	Fisheries and Oceans Canada	Health of Animals Act, Food and Drugs Act, Species at risk Act	26,308 tonnes (2019)
Other shellfish (clams, scallops)	Rafts, suspended lines, netting, hatcheries for seed	Prince Edward Island, Quebec, British Columbia	Onshore, nearshore	Boats, harvesting equipment, water quality monitoring, seeding	Yes	Fisheries and Oceans Canada	Health of Animals Act, Food and Drugs Act, Species at risk Act	318 tonnes (2019)

United States

Table 15. Information on aquaculture practices in the United States.

Species	Practice type (sea-pen, rack, artificial reef, etc.)	Location	Expansion plans for offshore operations	Energy requirements	Suitability for ocean renewable energy	Regulatory requirements	Other relevant market requirements (e.g., food safety criteria, sustainability, etc.)	Annual production
Finfish (salmon, trout, etc.)[47, 48]	Recirculating aquaculture system (RAS)	Onshore, nearshore	Yes - NOAA Aquaculture Opportunity Areas, starting with California and the Gulf of Mexico	Building operations onshore, feeding systems, RAS (pumps, filtration), boats	Yes (wave energy for offshore/ nearshore, tidal, OTEC in Hawaii). If stationed near marine areas, may use any nearshore renewable energy.	Projects sited in US waters must meet federal, state, and local regulations (environmental protection, water quality), building permits if onshore	Monterey Bay Aquarium Seafood watch Aquaculture Stewardship Council Best Aquaculture Practices (Global Aquaculture Alliance) FishWatch NOAA	Salmon: 17,000 tonnes (2018)
Eelgrass[49]	Natural recolonization, seeding, transplants	Onshore, nearshore, offshore		Boats, diving and replanting necessities, nursery facilities	Yes (wave energy for offshore/ nearshore, tidal, OTEC in Hawaii)	Permitting by Shellfish Interagency Permitting Team through JARPA		
Shellfish (oyster, mussel, clam, other)[50, 51, 52]	Rafts, suspended lines, netting, hatcheries for seed	Onshore, nearshore, offshore		Boats, diving equipment, lighting, water pumps, hatchery operation and maintenance	Yes (wave energy for offshore/ nearshore, tidal, OTEC in Hawaii)	Projects sited in US waters must meet federal, state, and local regulations (environmental protection, water quality), building permits	Monterey Bay Aquarium Seafood watch Aquaculture Stewardship Council Best Aquaculture Practices (Global Aquaculture Alliance)	Oyster: 20,000 tonnes (2018) Clam: 5,000 tonnes (2018) Mussel: 400 tonnes (2018)

47 https://media.fisheries.noaa.gov/dam-migration/fus_2018_report.pdf
48 www.epa.gov/sites/production/files/2020-03/documents/gulf_aquaculture_guide_oct2019.pdf
49 https://archive.fisheries.noaa.gov/wcr/publications/aquaculture/wa_eelgrass_and_shellfish_aquaculture_workshop_report_final_11-03-17.pdf
50 https://www.fisheries.noaa.gov/west-coast/aquaculture/commercial-shellfish-aquaculture-west-coast
51 https://www.fisheries.noaa.gov/content/national-shellfish-initiative
52 https://www.fisheries.noaa.gov/national/aquaculture/us-aquaculture

Coral, sponge[53, 54]	Using distinguishable substrate for culturing on the seafloor	Onshore		Boats, diving equipment, mechanical harvesting, storage before sale, habitat monitoring/ seabed inspection	Yes	Florida: Aquaculture Certificate of Registration from the Florida Department of Agriculture and Consumer Services (FDACS), U.S. Army Corps of Engineers Programmatic General Permit (SAJ-99)	Sovereignty Submerged Lands Lease Agreement for operations in EEZ	
Kampachi (Seriola rivoliana)[55]	Net pen	Nearshore, offshore (Hawaii)			Yes	Special Coral Reef Ecosystem Fishing Permit (SCREFP)		2,700 tonnes (2013)
Seaweed (bull kelp, sugar kelp, dulse, ribbon kelp)[56, 57]	seeding longlines	Nearshore		Boats, post-processing				

53 https://www.fisheries.noaa.gov/southeast/resources-fishing/permits-applications-and-forms-southeast
54 https://www.fdacs.gov/content/download/64592/file/FDACS-P-02062-Live-Rock-Aquaculture-Rules-and-Regulations.pdf
55 https://www.regulations.gov/docket/NOAA-NMFS-2015-0137
56 https://www.fisheries.noaa.gov/national/aquaculture/seaweed-aquaculture
57 https://projects.sare.org/sare_project/gs16-165/

South America

Chile

Table 16. Information on aquaculture practices in Chile.

Species	**Practice type** (net pen, rack, etc.)	**Location**	**Conditions of operation**	**Expansion plans for offshore operations**	**Energy requirements**	**Suitability for ocean renewable energy**	**Regulatory requirements**	**Other relevant market requirements** (e.g., food safety criteria, sustainability, etc.)
Finfish (mostly *Salmo salar* and *Oncorhynchus kisutch*)	Sea pen	Channels and fjords of southern Chile (Chiloé Archipielago to Magellan Strait)	Most locations are sheltered with currents >0.5m/s. Some locations are more exposed to ocean swell, and some are exposed to larger tidal ranges and currents.	The Chilean Government and industry have intentions to expand offshore. Currently, two industry consortiums (with government funding) are working on the technological challenges of moving offshore.[58]	Most farms include a floating structure (pontoon) with permanent crew (4-10 people) and feeding equipment (4-12 silos with feeding dozers and blowers). Each blower has typically 22.5 kW motors and operates 2-6 hours/day.	Ocean energy can be suitable for some farms today, on a case-by-case basis and likely only for a small portion. In the future this may change if offshore aquaculture becomes a reality. We see a very large potential for floating wind and (if energy cost allows) wave energy.	For current farms, requirements are not complex. If the existing maritime concession is large enough to allocate the ocean energy device, is even more simple. Offshore aquaculture is still not completely regulated and government and industry are working on this, but I don't think this should be a problem as long as the size of the ocean energy device is relatively small and energy is used locally.	Yes. Chile's channels, fjords and all inners seas of Patagonia are very unique environments and salmon farming has had evident negative effects on ecosystems and both positive and negative effects on local population. Joint efforts to minimize this are very important and offshore faring can contribute to reduce the pressure over these regions, reducing density and perhaps moving to the north.

58 http://innovaoceanica.cl/; https://ecoseafarming.com/

Shellfish – Mussels[59] (*Mytilus chilensis*)	Long line	Channels and fjords of southern Chile (Chiloé Archipielago)	Most locations are sheltered with currents >0.5m/s. Some are exposed to larger tidal ranges and currents.	Mussel aquaculture is still a small scale, minimally industrialized business. Expansion plans, but only for operations in the same sheltered areas as today.	Sowing and harvesting can require energy. These machines use small stationary engines between 8-15kW. Harvesting machines can harvest up to 7t / hour.[60]	Since harvesting and sowing only occur for very short periods during the year, suitability of offshore energy is very limited.	Standard permits for allocation of moorings, buoys, and longlines.	Shellfish aquaculture has a very important social role and is perceived as more sustainable than salmon farming. Most companies are small family-owned, local companies, very different to salmon companies.
Shellfish – Scallop (*Argopecten purpuratus*)	Lantern nets	Near-shore, along the Chilean coast, mainly in the north	Sheltered locations (bays)	Expansion plans to more southern regions of Chile, in sheltered areas.	No energy requirements known, besides small winches.	No suitability so far	Similar to mussel permits	Similar to mussel farms
Shellfish – Oyster (*Ostrea chilensis* and *Magallana gigas*)	Lantern nets	Near-shore, along the Chilean coast, mainly in the south. Channels and fjords of southern Chile (Chiloé Archipielago)	Most locations are sheltered with currents >0.5m/s. Some are exposed to larger tidal ranges and currents.	Expansion plans to northern regions of Chile, in sheltered areas.	No energy requirements known, besides small winches.	No suitability so far	Similar to mussel permits	Similar to mussel farms
Seaweed. Mainly *Agarophyton chilensis*	Longlines	Near-shore, along the Chilean coast, mainly in the south. Channels and fjords of southern Chile (Chiloé Archipelago)	Sheltered locations (bays)	Expansion plans all along the coast. Still very small (3.5%) compared to total (wild) seaweed extraction.	No energy requirements known, besides small winches.	No suitability so far	Similar to mussel permits	Similar to mussel farms

59 https://www.amichile.com/ (Spanish only); http://intemit.cl/ (Spanish only)
60 http://acerostecsur.cl/productos/linea-mejillon/maquinaria-de-cultivo.html

Oceania

Australia

Table 17. Information on aquaculture practices in Australia.[61]

Species	Practice type (sea-pen, rack, artificial reef, etc.)	Location	Expansion plans for offshore operations	Suitability for ocean renewable energy	Annual production
Crustaceans – prawn, yabby, kuruma prawn, mud crab, red claw crayfish	Land-based hatcheries, recirculation aquaculture systems, grow out pond systems and processing facilities. Semi-intensive.	Land based	No plans	Not suitable	6,823 tonnes
Shellfish – abalone, blue mussels, rock oyster, Pacific oyster, native oyster, silver lipped pear oyster, blacklip oyster	Abalone – tanks Mussels – longline system Oysters - stick cultivation, tray cultivation, longline, rack and basket system	Abalone – land based Mussels – sub-tidal system, nearshore hatcheries Oysters – sub-tidal system, nearshore and land-based hatcheries, nearshore coastal grow-out	No plans	Not suitable	14,812 tonnes
Finfish (onshore) – barramundi, murray cod, rainbow trout, silver perch, Australian bass, eel tailed catfish, golden perch, jade perch	Land based hatcheries and intensive recirculation aquaculture systems, pond systems	Land based	No plans	Not suitable	10,181 tonnes
Finfish (marine) – southern bluefin tuna, yellowtail kingfish, Atlantic salmon	Tuna – ranching, sea-cage aquaculture Others – land-based hatcheries, land based grow out or sea-cages	Tuna – offshore Others – land based, nearshore, and offshore grow out operations	Tuna – operations are currently offshore Plans to move salmon operations offshore	Suitable for ocean energy	78,162 tonnes

61 https://www.dpi.nsw.gov.au/fishing/aquaculture/publications/aquaculture-production-reports; https://www.publications.qld.gov.au/dataset/aquaculture/resource/bb9b4fd4-7fe3-43ff-b7e6-29c73ed45b03; https://www.pir.sa.gov.au/aquaculture/publications; https://www.fish.wa.gov.au/Documents/sofar/status_reports_of_the_fisheries_and_aquatic_resources_2018-19.pdf; https://dpipwe.tas.gov.au/Documents/DPIPWE%20Annual%20Report.pdf; https://www.uts.edu.au/sites/default/files/2020-06/uts-fass-victoria-fisheries-aquaculture-report.pdf

French Polynesia

Table 18. Information on aquaculture practices in French Polynesia.[62]

Species	Practice type (sea-pen, rack, artificial reef, etc.)	Location	Expansion plans for offshore operations	Suitability for ocean renewable energy	Regulatory requirements	Annual production
Crustacean – shrimp	Land-based tanks; floating cages in lagoon	Land-based/ nearshore	No	No		140.6 tonnes (2019)
Finfish – Paraha peue	Floating cages in lagoon	Nearshore	No			13 tonnes (2019)
Shellfish – giant clam	Hatcheries; collect individuals on adapted support		No		Minimum size for commercialization	
Oyster (pearl farming)			No			13 tonnes (2018)

62 https://www.ispf.pf/docs/default-source/publi-pf-bilans-et-etudes/peb-laquaculture-en-polyn%C3%A9sie-fran%C3%A7aise-en-2019.pdf?sfvrsn=8 (in French)

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