

# Environmental effects of marine renewable energy off-grid and micro-grid applications: a use case approach to assess existing knowledge and remaining uncertainties

Lenaig G. Hemery, Linnea Weicht, Kristin Jones, Jacob McGrath, Curtis Anderson, Andrea E. Copping, Lysel Garavelli

**Abstract**— Most environmental research and monitoring for marine renewable energy (MRE) devices has focused on effects that will drive consenting and licensing decisions for large, utility-scale projects. However, many uses of MRE will be to power remote coastal and island communities via micro-grids, or provide power at sea for ocean observations, offshore aquaculture, and other off-grid uses. Community-scale MRE energy generation will require transmitting the power to shore via an export cable, while power-at-sea uses will generate and use the power without connection to shore. These applications are likely to operate on smaller scales than utility-scale MRE devices. There has been little focus on the potential environmental effects for these increasingly more common micro-grid or off-grid uses. The smaller MRE devices are likely to have different, and possibly lesser, environmental effects than large-scale MRE projects. Here, we generated a series of hypothetical micro-grid and off-grid use cases, some with community-scale power use and others strictly power-at-sea. For each use case, we compiled a physical description of the deployment area, details about the likely MRE technology, and information about the end uses and power needs. We inventoried the species of regulatory concern, commercial and recreational species, important habitats, potential environmental interactions with an MRE system, and potential socio-economic benefits or concerns. While some use cases were taken from developing projects, none represent projects yet in the water. This use-case approach enabled an initial assessment of potential environmental effects, based on location and scale of the projects, which could help inform regulatory decisions.

**Keywords**—Consenting, environmental effects, micro grid, off grid, power at sea, remote communities.

## I. INTRODUCTION

WHILE marine renewable energy (MRE) was initially developed for utility-scale applications, as an alternative form of renewable energy for coastal areas with access to suitable wave or tidal resources, micro-grid and off-grid uses have become realistic market applications [1]. Micro-grid refers to community-scale MRE projects, whether they provide electrical power to a remote community, specific application like water desalination, or backup generation for disaster recovery [1]. Examples of operational micro-grids include the Igiugig Hydrokinetic Project with two RivGen turbines in the Kvichak River to power the Igiugig Village in Alaska (U.S.) in replacement of fossil fuel generators [2], and the D10 Tidal Turbine installed off Ushant Island in Brittany (France) that has been supplying 25% of the power consumed on the island [3]. Other remote communities are actively looking at implementing MRE to power part or all of the community's needs [4]. Off-grid refers to power-at-sea applications, whether it is for powering ocean observation and navigation buoys, recharging autonomous vehicles, or powering marine aquaculture operations [1], [5]. While very few systems are currently operational [6], scientists and engineers are developing various prototypes [7], [8].

Micro-grid and off-grid MRE projects are expected to be of much smaller size (i.e., device dimensions, nameplate capacity, footprint of mooring systems) than utility-scale devices. As such, it is anticipated that environmental effects of micro-grid and off-grid projects may be lesser

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than those of large-scale MRE developments. The current framework for assessing MRE environmental effects relies on knowledge from utility-scale projects and uncertainties remain on whether this framework is fully applicable to micro-grid and/or off-grid applications. Seven main stressor-receptor interactions of concern, where stressors are the devices or parts of the system that may cause stress, injury, or death to receptors (marine animals, habitats, and ecosystem processes), have been identified by the regulatory and research community internationally for utility-scale MRE projects [9]:

- Risk of collision of marine animals with moving parts of tidal, riverine, or ocean current turbines.
- Effects of underwater operational noise from devices on animal behavior and essential sensory capabilities.
- Effects on sensitive animals of electromagnetic fields (EMFs) from energized cables and other device parts.
- Changes in the benthic and pelagic habitats that support marine animals.
- Entanglement of large marine animals in mooring lines or underwater cables associated with devices.
- Changes in oceanographic systems due to effects on ocean circulation, wave height, or energy removal.
- Displacement of marine animals from their usual habitats or migratory routes due to the devices.

In countries regulating potential environmental effects of MRE development, scientific knowledge and remaining uncertainties regarding possible effects on threatened species and vulnerable habitats, as well as on socio-economic aspects, have been driving the consenting and

licensing processes, directing targeted monitoring and/or mitigation measures. Whether micro-grid and off-grid applications will undergo a similar level of regulatory and scientific scrutiny remains to be evaluated.

The goal of the study presented here was to develop a variety of hypothetical, though realistic, use cases of micro-grid and off-grid MRE applications and assess the potential environmental and socio-economic effects of such projects. From there, considerations on specific environmental monitoring needs, mitigations measures, or other consenting requirements are drawn, in comparison to those of utility-scale MRE projects.

## II. METHODS

For the purpose of this assessment, 12 use cases were generated, six focused on remote community power needs and six focused on power at sea. The use cases were chosen to represent a wide range of power needs, applications, locations, and environments that make up the diversity of micro-grid and off-grid applications (Fig. 1). For instance, in one use case, MRE would be used to electrify a small coastal village, while in another use case MRE would be used to provide backup power to an island community. In other use cases, the energy would be used at sea to power a coastal weather buoy, an integrated ocean observation buoy, or an offshore aquaculture fish farm. While these use cases remain hypothetical, several of them were informed by existing or developing projects or concepts described in the scientific literature, though none are currently deployed.

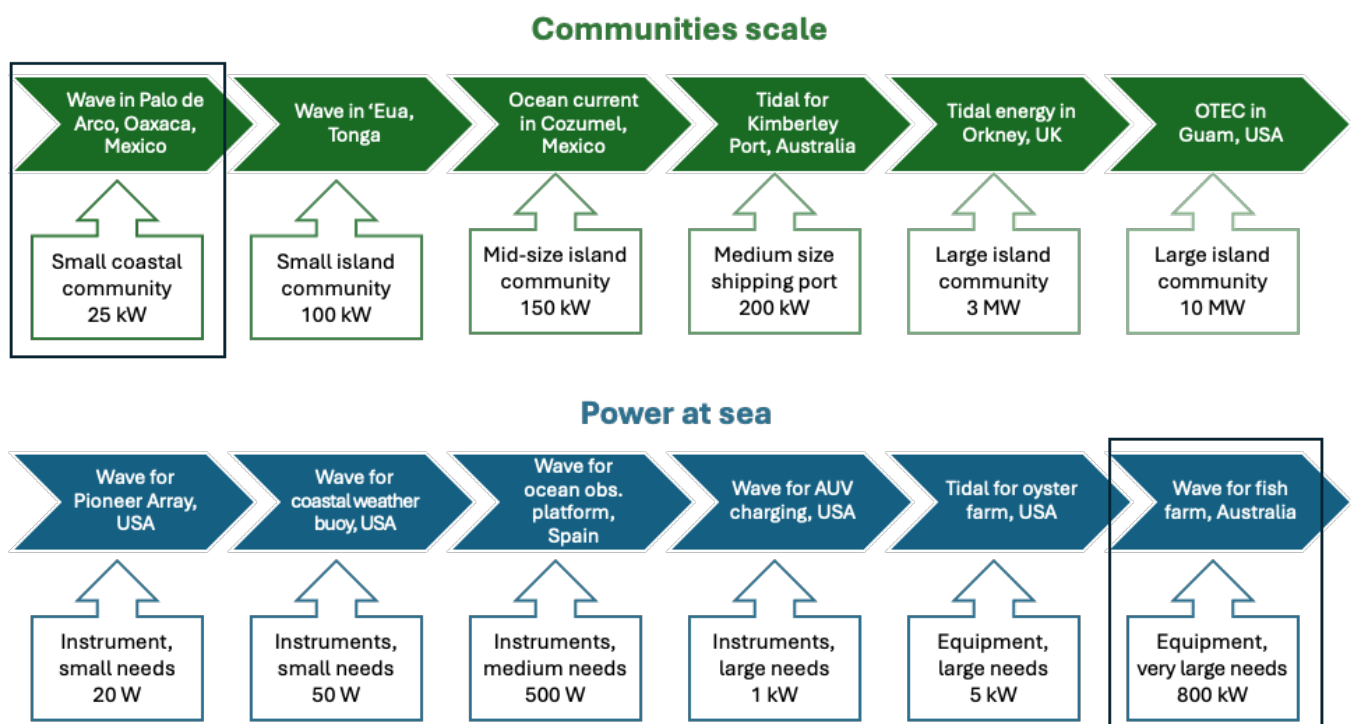


Fig. 1. The 12 micro-grid and off-grid use cases assessed for this project, separated into community-scale applications and power-at-sea applications, with nameplate capacity of proposed devices. The two use cases described in this paper (“Wave in Palo de Arco, Oaxaca” and “Wave for fish farm, Australia”) are shown by the black boxes.

For each use case, information was compiled to create the technological framework of the use case (Table I). Information about end uses and power needs, community description and values (e.g., reliance on fossil fuels) in the case of a community use case, and physical description of the deployment area, was gathered from various websites and literature available online. The most suitable MRE technology type (i.e., wave, tidal, ocean current, or ocean thermal energy conversion [OTEC]) for each use case was selected with a specific archetype where appropriate (e.g.,

oscillating water column, cross-flow turbine, etc.) and nameplate capacity most suited to the power needs and site characteristics. Additional details related to the technology included the resource range for ideal power, expected power production, device position in the water column, type of contact with the seafloor, size of footprint on the seafloor, mooring system, type of export cable, and expected levels of underwater noise and electromagnetic fields emissions (Table I).

TABLE I  
TECHNOLOGICAL INFORMATION COMPILED FOR THE MICRO-GRID (COMMUNITY SCALE) AND OFF-GRID (POWER AT SEA) USE CASES.

End uses and power needs	Community description and values	Deployment area physical characteristics	Technology details
<b>Community scale:</b> <ul style="list-style-type: none"> <li>Population size</li> <li>Average power needs</li> <li>Existing power sources</li> </ul> <b>At-sea instruments:</b> <ul style="list-style-type: none"> <li>Instrument/sensor types</li> <li>Power consumption</li> <li>Existing power source</li> </ul> <b>Other applications:</b> <ul style="list-style-type: none"> <li>Power needs</li> <li>Existing power sources</li> </ul>	<ul style="list-style-type: none"> <li>Isolation from national or regional grid</li> <li>Activities needing power</li> <li>Reliance on fossil fuels</li> <li>Support for renewables</li> <li>Ocean-oriented activities</li> <li>Ocean-based economy</li> </ul>	<ul style="list-style-type: none"> <li>Geographic location</li> <li>Available MRE resources</li> <li>Distance from shore</li> <li>Bathymetry</li> <li>Seafloor type</li> <li>Cable landing area</li> </ul>	<ul style="list-style-type: none"> <li>MRE type</li> <li>Resource range for ideal power</li> <li>Power produced</li> <li>Device position in water column</li> <li>Type of contact with seafloor</li> <li>Footprint size on seafloor</li> <li>Mooring line number &amp; type</li> <li>Underwater noise levels</li> <li>Power export cable</li> <li>Electromagnetic field levels</li> </ul>

Environmental and socio-economic information was also gathered for each use case to create the environmental framework (Table II). This information comprised lists of species and habitats of concern in the area of a use case, as well as other uses of the area, any place-based specificities, or Indigenous peoples' values. Any potential interactions between the species or habitats of concern and the MRE system proposed for each use case (as described in [9]), as well as potential socio-economic benefits or concerns, were identified from the intersections of the technological and environmental frameworks. Finally, recommendations

were drawn from the information gathered and analysed for each use case for environmental monitoring needs, potential mitigation measures, and potential consenting specificities for each off-grid or micro-grid application (Table II). The Management Measures Tool for Marine Energy, accessible on Tethys [10] was leveraged to identify applicable mitigation measures, as well as the country-specific Guidance Documents for Risk Retirement [11] that tie each use case with the regulatory context for MRE for the countries in which they are set.

TABLE II  
ENVIRONMENTAL AND SOCIO-ECONOMIC INFORMATION COMPILED FOR THE MICRO-GRID (COMMUNITY SCALE) AND OFF-GRID (POWER AT SEA) USE CASES.

Species/habitats of concern	Environmental interactions	Socio-economic effects	Recommendations
<ul style="list-style-type: none"> <li>Threatened and endangered species</li> <li>Commercial species</li> <li>Recreational species</li> <li>Cultural species</li> <li>Sensitive habitats</li> <li>Protected areas</li> </ul>	<ul style="list-style-type: none"> <li>Collision risk</li> <li>Underwater noise</li> <li>Electromagnetic fields</li> <li>Changes in habitat</li> <li>Entanglement risk</li> <li>Oceanographic systems</li> <li>Displacement</li> <li>Others</li> </ul>	<ul style="list-style-type: none"> <li>Other uses of the area</li> <li>Place-based specificity</li> <li>Indigenous people's values</li> <li>Potential benefits</li> <li>Potential concerns</li> </ul>	<ul style="list-style-type: none"> <li>Environmental monitoring needs</li> <li>Potential mitigation measures</li> <li>Potential consenting specificities</li> </ul>

### III. RESULTS

While 12 use cases were developed for this study, this paper focuses on two of them: wave energy for a small coastal community in Oaxaca, Mexico; and wave energy to power an offshore fish farm in Tasmania, Australia (Fig. 1).

#### A. Wave energy for a remote community in Oaxaca, Mexico

##### 1) Technological framework

The locality of Palo de Arco, in the municipality of San Pedro Pochutla, on the Pacific coast of Oaxaca, Mexico, is a small coastal community of 22 residents in six households in the hills above the coastline, not connected

to an electrical grid [12]. Other small communities nearby are also lacking connection to utilities. Based on electricity usage in nearby electrified communities, the average household power consumption is around 100 kWh/month, used for lighting, cooking, refrigeration, and laundry [13]. The climate in Oaxaca is mild, with little need for heating and cooling, contributing to less electricity usage than other parts of the country. Residents without electricity in the area currently rely on wood-burning stoves for cooking, and candles, oil lamps, or lamps with disposable batteries for lighting [14]. Regional energy needs in the coastal area of Oaxaca are primarily supplied by two oil refineries and power plants that generate a combined 640 MW of power to the region. The state of Oaxaca also produces around 50 MW of onshore wind energy. MRE adds a unique value proposition for small coastal communities like Palo de Arco.

While tidal, ocean current, or salinity gradient energy are not available MRE resources for the coastal area of Oaxaca, OTEC and wave energy appear more suitable [15]. However, OTEC is currently not scalable in an affordable way to the limited energy needs of a small remote community like Palo de Arco. Conversely, wave energy can be extracted by small-scale devices adapted to the local needs and the 10–20-kW/m wave energy availability found along the Oaxacan coast (Fig. 2).

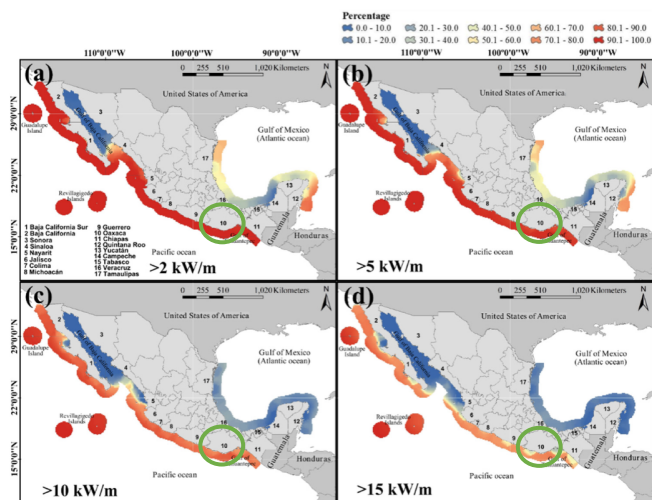


Fig. 2. Theoretical results of wave power availability in Mexico, in percentage of days in a 5-year period over the thresholds of 2 kW/m (a), 5 kW/m (b), 10 kW/m (c), and 15 kW/m (d). The state of Oaxaca is circled in green, along the south Pacific coast. [15].

Consequently, for this use case a 2-m-diameter single-body point absorber wave energy converter (WEC) could produce a maximum power of 25 kW, with an average power of 5 kW sustainable year-round with the wave climate found at a short distance from the Oaxacan coastline [16]. The point absorber would include a surface float and be anchored to the seabed by a single-point mooring line and 1-m<sup>2</sup> deadweight or gravity anchor, enabling the device to move freely with the waves [17]. The device would be located in no more than 50 m of water depth and a 240-kV alternating current (AC) underwater

cable would run along the seafloor, buried 1-m deep into the soft sediment seafloor, to export the power to a small shore-based substation (Fig. 3). The magnetic field strength can be calculated using the mathematical expression of Ampere's Law [18]. At peak power (25 kW), the magnetic field emitted from the cable would reach 20.85 nT·m, reducing with distance radially away from the cable. A point absorber of this size would be expected to produce short pulses (0.2–0.6 s) of low level operational radiated underwater noise, in frequencies below 1 kHz, with peak amplitudes around 150 Hz [19].

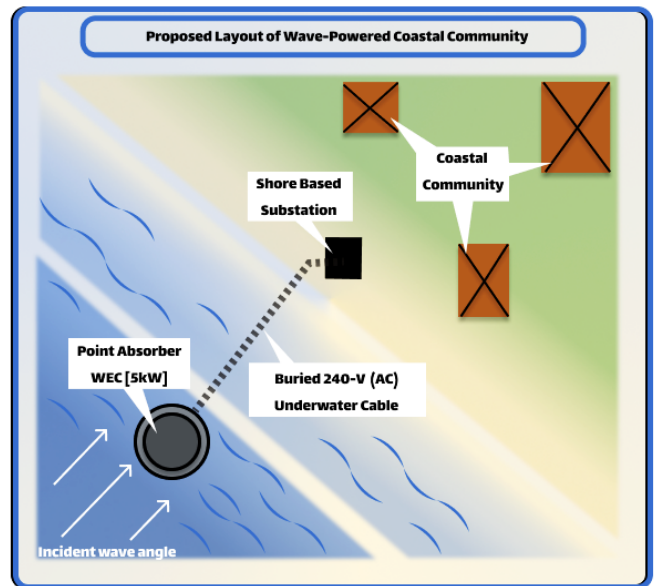


Fig. 3. Rendering of the hypothetical point absorber wave energy converter (WEC) supplying power to the coastal community at Palo de Arco, Oaxaca, Mexico.

## 2) Environmental and socio-economic framework

The coastal waters of Oaxaca are home to a large diversity of species, many of which are listed as threatened, sometimes because of their endemism to the area. 18 species of marine mammals have been observed off the coast of Oaxaca, year-round or seasonally [20]. All 18 species of marine mammals have special protection status in Mexico, but only two are listed by the International Union for Conservation of Nature (IUCN) as threatened: blue whales (endangered) and sperm whales (vulnerable). Three species of sea turtles are known to nest on Oaxacan beaches, especially at La Escobilla about 50 km north of Palo de Arco, and benefit from strict legal protection as they are in danger of extinction: green sea turtles, leatherback sea turtles, and olive ridley sea turtles [21]. The coastal waters of Oaxaca are frequented by multiple species of seabirds under special protection status, such as boobies, shearwaters, and storm petrels that are listed as threatened, and the endemic Townsend's shearwater listed in danger of extinction. Potentially found in nearshore areas, the Kentish plover is listed as threatened and the American oystercatcher is in danger of extinction [20]. While two species of elasmobranchs are listed as threatened (whale sharks and largetooth sawfish), three reef-associated teleost fish species benefit from

special protection status (king angelfish, Cortez angelfish, and Pacific seahorse) [21]. Lastly, four invertebrate species (spiny oysters, cup-and-saucer snails, giant Mexican limpets, and brown sea cucumbers) are listed with special protection.

Lagoons throughout coastal Oaxaca are home to vast stretches of black, red, white, and buttonwood mangroves, which provide foraging, rearing, and/or breeding habitats for numerous species. Coral reefs are also common along the coastline, especially in the southern part of the state. Some of these sensitive habitats are protected as part of the Lagunas de Chachahua and the Huatulco national parks, protecting respectively an estuarine area  $\approx$  150 km north of Palo de Arco, and coral reefs  $\approx$  30 km south [22].

Because of its abundant biodiversity, coastal Oaxaca is home to important shrimp and tuna fisheries, various small-scale artisanal fisheries, and three aquaculture facilities [23]. In 2024, the commercial fishing industry represented 368 workers and 92 fishing vessels [24]. Fish species of commercial, recreational, and cultural interest include mahi-mahi, skipjack, snappers, horse mackerel, and albacore tuna. Fishing tourism is also an important part of the local economy, as well as ecotourism at the coastal national parks and sea turtle sanctuaries [25]. Other leading maritime industries in Oaxaca include offshore oil extraction and deep-water ports for transportation of oil, commerce, fisheries, and tourism [25]. In addition, coastal resources provide valuable social benefits to the local communities, such as subsistence fishing [26]. Zapotec and Huave peoples are the largest Indigenous coastal communities in the state of Oaxaca (respectively 75% and 3% of all Indigenous people in the state), both valuing the ocean in their ceremonies and rituals [27].

Potential environmental effects of a point absorber and associated infrastructure of the scale described for this use case would be expected to be limited because of the small space that the device would occupy in the water column and narrow footprint it would have on the seafloor. Like most artificial structures at sea, the point absorber and its mooring system would be colonized by seaweeds and invertebrates. It could become overtime a small artificial reef, providing food and shelter to reef-associated fishes like the protected king and Cortez angelfishes, as well as attracting predator species like snappers around the seafloor structures, or pelagic fishes like tuna and mahi-mahi around the surface float. Collision risk would not be expected with a point absorber since it does not have rotating blades. Because the mooring lines and export cable would be taut with no loose ends, entanglement would also be unlikely. Some benthic elasmobranchs, like the largemouth sawfish, could display some behavioral changes (e.g., attraction, avoidance) near the power export cable, though very low levels of EMFs would be expected from such a small point absorber. Because the cable would be buried in soft sediment, it would add some shielding to the cable and reduce EMF exposure. The underwater noise emissions may fall within the hearing range of animals

that would swim in the vicinity of the device, but the narrow frequency range and low intensity of noise emissions would not be expected to harm the animals. However, the noise might create a distraction or annoyance that may slightly displace some sensitive animals, like marine mammals and sea turtles, to avoid the device area. Finally, large-scale displacement of animals and changes to oceanographic systems would be unlikely with a single wave energy device, especially of this size.

Deploying a small point absorber WEC off the coast of Palo de Arco would lower the energy costs for this small and isolated community and improve their energy sovereignty, while decreasing their reliance on fossil fuels and potential risks of pollution. The presence of the WEC may also provide training and employment prospects for local workers to maintain the infrastructure. Recreational fishing and/or ecotourism opportunities may be created in association with the device. On the other hand, spatial conflicts may arise with local fishers or other sea users in the area. Perceptions of potential impacts to sea turtles and their nesting habitats may bring opposition from some, as well as perceptions of potential visual effects. Potential impacts to Indigenous cultural resources during installation, for instance of export cables at sea and on land, could also raise some concerns.

### 3) *Recommendations for this specific use case*

To assure full support from the local community, the point absorber project would need to be brought forward by community members, or at minimum proposed in collaboration with community members, with input from all involved in the community. Such a community-led project would enable maximizing the social-economic benefits while minimizing any impacts. Specific mitigation measures may be helpful to implement, like timing both marine- and shore-based construction activities to avoid times of particular sensitivity (e.g., sea turtle nesting), or covering the cable with locally sourced materials in areas where burial may not be possible [10]. Once the project is operational, environmental monitoring would include measuring the acoustic signature of the device following international technical specifications [28], as well as measuring the level of EMFs along the cable route. Occasional monitoring of the biological growth on the device and mooring system would need to be performed, to clean out excessive growth that would limit the point absorber's performance. Such maintenance operations would enable checking for the potential presence of non-native species and the use of the new artificial reef by species with protection status. To make sure that proper consents and licenses are obtained for this hypothetical use case, project proponents would be advised to follow the guidance described in the manual for ocean energy project permits [29]. Specifically, the project would need to be compliant with various articles of law listed in Table III.

TABLE III

MEXICAN LAWS AND ARTICLES POSSIBLY RELEVANT TO THE USE CASE.

Mexican law	Articles	Reference
Federal Law of the Sea	23–56	[30]
General Law of National Assets	119–127	[31]
General Law of Wildlife	56–67	[32]
General Law of Ecological Equilibrium and Environmental Protection	5–8, 19–20, 44–87, 117–133	[33]
General Law of Sustainable Fisheries and Aquaculture	32–35	[34]
Law of National Waters	9–12, 85–120	[35]
General Law of Human Settlements, Territorial Ordinance and Urban Development	All articles	[36]

## B. Wave energy for offshore aquaculture in Tasmania, Australia

### 1) Technological framework

Farming marine species (e.g., fish, shellfish, algae) in the ocean presents an opportunity for harvesting sustainable protein without land or river development. Aquaculture is a sizeable industry in Australia, and salmonid farming is the largest aquaculture sector in the country, with 98% of the fish grown in Tasmania because of temperature and quality of the water [37]. Current Atlantic salmon marine farms in Tasmania are located in sheltered coastal areas, where they can be connected to the local electrical grid, although most are powered by diesel generators for their daily operations [37]. However, a growing number of aquaculture companies want to expand their operations to offshore locations, exposed to more energetic waters. For offshore farms, diesel generators on the feed barges would need to provide power for fish feeding, ventilation, and on-site freshwater bathing, as well as lighting and other uses, like potential for vessel charging. Total energy needs for an offshore Atlantic salmon farm would be over 15,000 kWh/day, corresponding to a power consumption of 625 kW [38]. This includes daily stationary electrical demands of a feed barge (6 MWh/day, or 250 kW average continuous power) and energy associated with transporting feed components and fuel for generators (9 MWh/day or 375 kW average continuous power). The energetic waters offshore could provide power for an offshore salmon farm with MRE to alleviate the reliance on fossil fuels.

The southern coast of Australia is exposed to powerful Southern Ocean swells, resulting in an estimated 1,455 TWh/year of available wave energy at the ocean's surface following the 25-m depth contour along the southern coast [39]. The annual mean wave resource availability several nautical miles offshore of Tasmania, where offshore aquaculture operations could be sited, reaches up to 75-80 kW/m, corresponding to significant wave heights of up to 3.5 m (Fig. 4) [40], [41]. To optimize space, an oscillating water column (OWC) WEC could be added to an offshore aquaculture feed barge moored at a depth of 25 m on soft bottom habitat off the southeast coast of Tasmania. The

change in air pressure inside of a chamber in the device, due to wave heave movement under the barge, would drive an air turbine and produce electricity. A 21x24-m OWC located in a wave resource with a power potential of 75 kW/m would produce around 400 kW average power, requiring at least two devices to produce enough power for a three-pen offshore salmon farm (Fig. 5), if considering both stationary and transportation-related energy. Replacing only stationary power requirements would only necessitate two OWCs, with one being a backup for energy reliability. If paired with the feed barge, the first OWC would leverage the barge's four-point mooring system and power export cables supplying electricity to the equipment would be on the barge itself, eliminating marine animals' exposure to EMFs. A second and third OWC would be placed on separate barges and moored near the feed barge, as pictured in Fig. 5. Battery backup would also be needed to store excess power for occasions when waves are low. Power from the two additional OWCs would be passed to the feed barge via cables suspended in the water column. Each draped cable, at 240 kV AC, would produce a magnetic field of 336 nT\*m, with field strength reducing with distance radially away from the cable. As an OWC air turbine operates above water, while above-water noise may be high, underwater noise emissions would be reduced to low levels unlikely to affect marine animals.

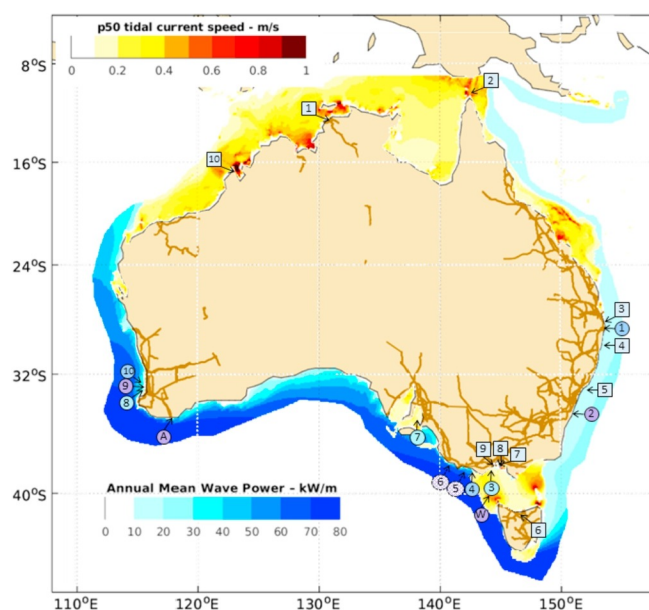


Fig. 4. Annual mean wave power availability and tidal current speed in areas surrounding the Australian coast; Tasmania (island in the southeast) has large wave power along the south shore [41].

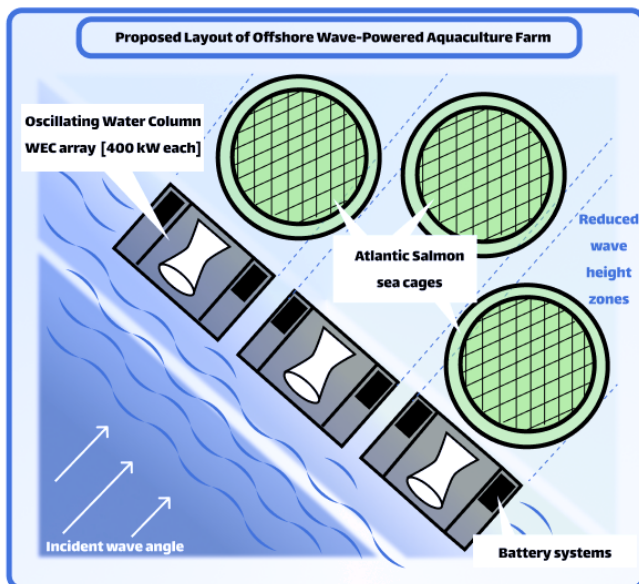


Fig. 5. Rendering of the small wave energy converter (WEC) array to power a hypothetical Atlantic salmon fish farm off the southern coast of Tasmania, Australia.

## 2) Environmental and socio-economic framework

The waters around Tasmania have a rich and endemic biodiversity, and many species are listed as vulnerable, endangered, or critically endangered at the State level or Commonwealth level [42], [43]. Several protected species of marine mammals can be encountered in the waters over the continental shelf around southeastern Tasmania [43]: long-nosed and subantarctic fur seals (respectively rare and endangered), southern elephant seal (endangered), blue whale (endangered), southern right whale (endangered), fin whale (vulnerable), and sei whale (vulnerable). Loggerhead (endangered) and leatherback (vulnerable) are the only two sea turtle species that would potentially inhabit these colder waters, however they are not known to nest on the local beaches [44]. There are 31 coastal or marine bird species of concern that visit the Tasmanian coast, including shorebirds, pelagic seabirds, and waders; two of these bird species are listed as critically endangered: eastern curlew and curlew sandpiper [42]. Among the 17 fish species of concern found in the coastal waters around Tasmania, nine are endemic to the island and three species of handfish, found in southeastern Tasmania, are listed as critically endangered: spotted, Ziebell's, and red handfishes [42]. The great white shark (vulnerable) is the only protected elasmobranch species in southeastern Tasmania. While the Maugean skate is endangered, it is endemic to the west coast of the island [42]. Among invertebrates, the Tasmanian live bearing sea star and Bruny Island sea star are two endangered species present in southeastern Tasmania [43].

Southeastern Tasmania is the location of the George III Rock fishery research area, the Ninepin Point marine reserve, and the shark refuge area in the D'Entrecasteaux Channel. In addition, the Huon Marine Park is located directly south of the use case area and the Tasmanian Fracture Marine Park further west [45].

The ocean conditions and abundant biodiversity of Tasmania support a significant commercial aquaculture and fisheries economy. Salmonid aquaculture contributed \$639 million in economic value and 5,188 jobs from 2020-2021 [46]. Recreational fisheries draw over 100,000 fishers and provide around 1,700 jobs annually [47]. Important commercial and recreational species include abalone, Australian salmon, Pacific oysters, rock lobster, and various scalefish [46]. Commercial and recreational gillnet fishing is most prevalent in southeastern Tasmania, the region representing half of all statewide gillnet catch [48]. However, climate-driven declines in fisheries employment have impacted the small coastal communities [49]. Other maritime industries in Tasmania are tourism, logistical support for Antarctic exploration, and maritime shipping. Annually, Tasmanian ports provide 8,000 jobs and contribute \$2.3 billion to the economy [47]. In addition, coastal Tasmanian landscapes hold significant spiritual value for Aboriginal communities such as the Palawa and Nuenonne peoples in southeastern Tasmania. Species of cultural value include abalone, limpets, and warreners. Specific coastal regions of cultural heritage include the D'Entrecasteaux Channel and the lower Huon estuary in southeastern Tasmania [50].

The absence of moving parts in the water from the three OWCs in this use case would mean that collision would not be a risk for marine animals. Because the OWCs would be placed on barges, scour and seabed disturbance would be minimal and restricted to the mooring systems. The export cable supplying power to the feed barge would be directly on the barge and not expose marine animals to EMFs. The draped cables from the other two barges, however, would emit some EMFs in the water column, which could alter the behavior of some sensitive pelagic species like sharks, sea turtles, and salmonids. The mooring lines would be taut, but the dynamic underwater cables would have some slack; however, neither would have loose ends, making entanglement in those lines and cables unlikely. Underwater noise from the three devices is unlikely to affect marine animals because they will be above water, isolated by the support barges. The installation of two additional barges and mooring systems would be likely to create habitat for invertebrates, seaweed and fouling organisms. This may, with time, create an artificial reef and provide shelter for various fish and associated predators. Because of their relatively large size, together the three OWC barges may create an area of reduced wave height directly in their lee (Fig. 5), which could protect the fish pens from stronger waves [51]. Cumulatively, the three OWC barges and the fish pens may add enough lines and structures in the water to potentially displace some marine species from the area directly around the offshore aquaculture facility.

Pairing these OWCs with a feed barge would reduce offshore aquaculture electricity costs and decrease reliance on fossil fuels. Associated reductions in pollution may have broad benefits for conservation efforts, ecotourism,

and fisheries production. The addition of the devices could provide training and employment opportunities for staff at the aquaculture facility, potentially benefiting local communities relying on maritime jobs. Recreational or tourism opportunities may also be created by the presence of the devices. However, the WECs and offshore aquaculture farm may contribute to spatial conflicts with maritime shipping or other ocean activities. While some effects may occur to species of commercial, recreational, or cultural value during installation and operation, siting, mitigation, and monitoring efforts would be maximized to minimize potential impacts.

### 3) *Recommendations for this specific use case*

The presence of dynamic power export cables between barges may trigger specific environmental monitoring due to the uncertainty surrounding the effects of EMFs on sensitive pelagic animals. Although cable burial would not be possible, bundling cables together, possibly with twists, would help reduce EMFs in the water column [10]. The dissipation of wave energy may also be monitored in the lee of the barges and fish pens to collect useful field data that would help reduce scientific uncertainty [10]. Water quality may also be monitored under the terms of the aquaculture farm's license. Wave energy production would be secondary to the salmonid aquaculture activities in a use case like this, meaning consenting and licensing would be driven by the aquaculture specificities. However, helpful core principles for engagement with stakeholders and Aboriginal communities are outlined in guidelines provided by the Australian Energy Infrastructure Commissioner [52]. Being within 3 nm from shore (25-m isobath), the project would fall under jurisdiction of the state of Tasmania and four specific legislations: Aboriginal Heritage Act [53], Environmental Management and Pollution Control Act [54], Major Infrastructure Development Approvals Act [55], and Tasmanian State Policies and Projects Act [56].

## IV. DISCUSSION

Many remote communities along coastlines and inland waters worldwide are not connected to reliable utility grids and depend on fossil fuel generators and wood stoves for electricity, cooking, and heating [1]. Providing access to reliable and sustainable sources of energy like MRE would increase these communities' energy independence and resilience [4]. While MRE resources near remote communities may not necessarily be the greatest for utility-scale energy generation, MRE devices can be engineered to harvest smaller waves or slower currents and still meet the energy needs of these remote communities. The same is true for power-at-sea uses, especially for oceanographic observation and navigation marker buoys in hard-to-reach areas like the Arctic Ocean [57], [58]. Off-grid applications far offshore, like autonomous vehicles recharge, may also have access to untapped MRE resources like internal waves [59]. As such,

micro-grid and off-grid MRE applications could provide endless development possibilities that have access to more diverse MRE resources than utility-scale projects.

Similar to the OWC on the feed barge in the offshore aquaculture use case presented here, many power-at-sea MRE projects are designed for power use at the site of production within the same structure, limiting the need for power export cables and the associated EMF emissions. However, not all off-grid applications will be exempt from cables, and draped cables in the water column between the MRE device and the power-using application may be common. Potential effects of EMFs from draped cables on sensitive pelagic animals need more scientific research to assess whether the emission levels are posing true risks to some species and identify potential mitigation measures to implement. Because of the smaller size of micro-grid and off-grid MRE devices, environmental effects from underwater noise emissions, changes in habitats, changes in oceanographic systems, and displacement are expected to be low, as well as those of EMFs from seafloor power export cables. The risk of animal collisions with off-grid or micro-grid MRE turbines will need to be assessed on a case-by-case basis, depending on the turbine design and species present in the area. As demonstrated with this study, the framework established to assess environmental effects of utility-scale MRE devices is suitable to evaluating the effects of micro-grid and off-grid applications too, as long as the specificities like location of power consumption or device size are carefully considered in the evaluations.

While more scientific research is necessary to investigate the true scale of the potential environmental and socio-economic effects of micro-grid and off-grid applications, employing a use case approach enables a first assessment based on the current scientific information available. The use case approach allows the identification of remaining uncertainties in the scientific knowledge, as well as potential environmental monitoring needs, applicable mitigation measures, or consenting requirements aligned with the legislation of each use case's country. While this study only presented two use cases, the project will develop the remaining ten use cases (see Fig. 1) in the future stages of this research. Eventually, this study will result in a comprehensive overview of the potential environmental and socio-economic effects of micro-grid and off-grid MRE applications and will lay out a path forward for addressing the remaining knowledge gaps.

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