10.0

Potential Environmental Effects of Marine Renewable Energy in Tropical and Subtropical Ecosystems

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Marine renewable energy (MRE), such as wave, tidal, ocean current, and thermal and salinity gradient, is under development in many parts of the world. However, studies examining the environmental effects of MRE have primarily focused on deployments in temperate regions and countries in the Northern Hemisphere. As MRE development expands into tropical and subtropical countries (between 35°N and 35°S), there is a need to examine the potential environmental effects specific to these regions and their unique habitats and species. Unlike temperate regions where wave and tidal energy resources dominate, tropical and subtropical regions can leverage five different types of MRE: wave energy, tidal energy, ocean current energy, ocean thermal energy conversion (OTEC), and salinity gradient energy.

While wave energy resources are generally much lower around the equator than in temperate regions, it is typically greater in subtropical regions than tropical regions (Rusu & Rusu 2021). Hotspots for wave energy within subtropical and tropical regions include Western Australia (Wimalaratna et al. 2022), South Africa (Lavidas & Venugopal 2018), off the west coast of South America (Eelsalu et al. 2024; Lucero et al. 2017), Southeast Asia (Li et al. 2022), and around islands in the northern and southern Pacific Ocean (García Medina et al. 2023) and southern Indian Ocean (e.g., Mauritius (Kamranzad et al. 2022)). As the MRE industry advances, developments in these tropical and subtropical regions may be considered. Several tropical and subtropical areas also have tidal resources, such as the northern coast of Brazil (González-Gorbeña et al. 2015), the western coast of Central and South America (e.g., Colombia (Osorio et al. 2016)), the northwestern coast of Australia (Penesis et al. 2020), and the western coast of Africa (Hammar et al. 2012). Several channels and straits in Southeast Asia present good tidal resources as well, particularly in Indonesia (Firdaus et al. 2020) and the Philippines (Abundo et al. 2023). Harvestable ocean currents are generated further offshore than tidal streams, from large currents like the Gulf Stream. The strongest ocean currents are generally located in tropical and subtropical areas, off the coast of Florida and in Asia from Japan to the Philippines (Barnier et al. 2020). Temperature gradients that provide enough thermal power capacity are non-existent in temperate regions but abound in tropical and subtropical regions (Nihous 2010). OTEC uses temperature gradients between warm surface waters and cold deep waters to produce energy. OTEC is especially regarded as a preferred source of renewable energy by tropical island countries with access to cold deep water close to shore (Osorio et al. 2016). Finally, areas with extractable salinity gradient energy resources are located in temperate, tropical, and subtropical regions but the greatest potentials are found along warmer coastlines, especially in the Caribbean Sea and in the Mediterranean Sea (Alvarez-Silva et al. 2016).

Although MRE projects have predominantly existed in temperate regions, some wave, tidal, ocean current, and OTEC projects have occurred over the last several decades in tropical and subtropical regions, with various device prototypes tested and full-scale projects planned or deployed. In tropical and subtropical regions, there have been several successful wave energy deployments over the years, such as the test deployments at the Wave Energy Test Site in Hawaii (United States [US]) and the Perth Wave Energy project (Australia). A few tidal energy projects have also been, or are being, considered in tropical and subtropical regions (e.g., Clarence Strait Tidal Energy Project north of Darwin [Australia], Hydrokinetic Energy in the Florida Keys [US], and Lombok and Larantuka Straits in Indonesia, and San Bernardino Strait in the Philippines). While a few ocean current energy projects are under investigation, notably in Florida and the Caribbean, only the IHI Ocean Current Turbine has been tested at different demonstration scales in the Kuroshio area off Japan, as well as a pilot project off Taiwan. Several OTEC plants are currently in operation (e.g., in Hawaii and Japan) and additional projects are being proposed, planned, or constructed in numerous other areas, including islands in the Caribbean. Finally, the potential for salinity gradient energy has been assessed in some tropical and subtropical regions such as Mexico (Marin-Coria et al. 2021), Australia (Helfer & Lemckert 2015), and Colombia (Roldan-Carvajal et al. 2021). So far, no salinity gradient energy development has occurred in tropical and subtropical regions.

Prior and existing MRE projects in tropical and subtropical regions are relatively sparse and most target wave energy resources (Figure 10.1). China has the highest number of MRE projects with wave, tidal, OTEC, and ocean current technologies, followed by Australia and Japan. Other MRE projects have been located in Bermuda, Chile, Mexico, French Guyana, Madagascar, Togo, Israel, South Korea, Indonesia, and the US.

Because of the lack of development and available funding in tropical and subtropical regions, the environmental effects of MRE development are not well studied and could potentially differ from those described in temperate regions. Tropical and subtropical regions host a diverse range of benthic and pelagic habitats such as coral reefs, mangroves, and seagrass beds that provide feeding, breeding, spawning, and nursing grounds for a wide variety of marine animals, including commercially important, endangered, and keystone species (Figure 10.2). Because many of these animals and habitats are already experiencing the disproportionate impacts of climate change, MRE development in tropical and subtropical regions may present additional risks that could contribute to reduced biodiversity and ecosystem resilience (Felix et al. 2019). Tropical and subtropical

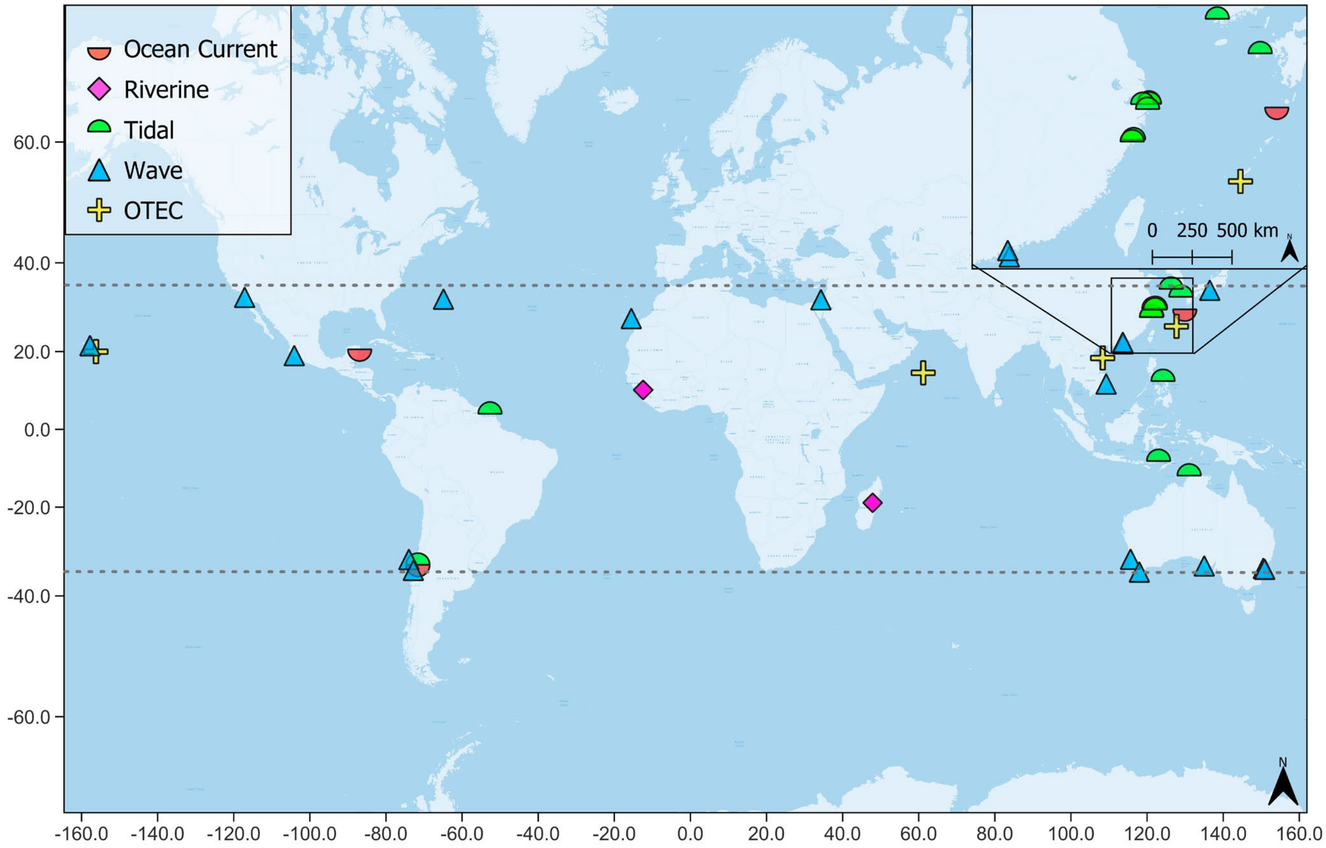

Figure 10.1. Marine renewable energy projects (ongoing, completed, canceled, planned) in tropical and subtropical countries, by technology type. The inset map highlights projects in China, Japan, and South Korea. Dashed lines represent the latitudinal range (35ºS to 35ºN) for the subtropical and tropical regions. Source: Tethys.

ecosystems also provide a variety of ecosystem services such as storm protection, recreational activities (tourism, fishery), and habitat for Indigenous communities (Moberg & Rönnbäck 2003). Mitigating environmental effects of MRE on these ecosystems is also important to support these benefits.

It is important to note that the adoption of suitable MRE technologies in tropical and subtropical regions will play an essential role in mitigating and adapting to the impacts of climate change. Deployed responsibly, MRE has the potential to make a substantial contribution to the provision of sustainable energy for communities and to the decarbonization of the wider energy system. This requires a better understanding of how environmental effects may differ between tropical/subtropical and temperate regions, to adapt, if necessary, technology and supporting infrastructure, operations, environmental mitigation, monitoring, and management methods. To begin addressing this need, Ocean Energy Systems (OES)-Environmental has expanded its research on the environmental effects of MRE to tropical and subtropical regions. The information presented in this chapter derives from a literature review, answers to a public survey, feedback collected from workshops, and interviews with experts in the field. The detailed methodology to collect the information as well as the public survey and interview questions are both available online as supplementary material. The public survey, available in both English and Spanish, requested information on any ongoing or emerging MRE projects in tropical and subtropical ecosystems, any research, monitoring, or modeling efforts that may be relevant, any relevant literature or other resources of information, and any specific contacts and/or organizations with relevant experience in these areas. The interviews with experts requested similar information as the survey and were also used to identify knowledge gaps and determine future research needs on environmental effects of MRE in tropical and subtropical ecosystems. The information collected on each topic area is covered thematically in the following sections.

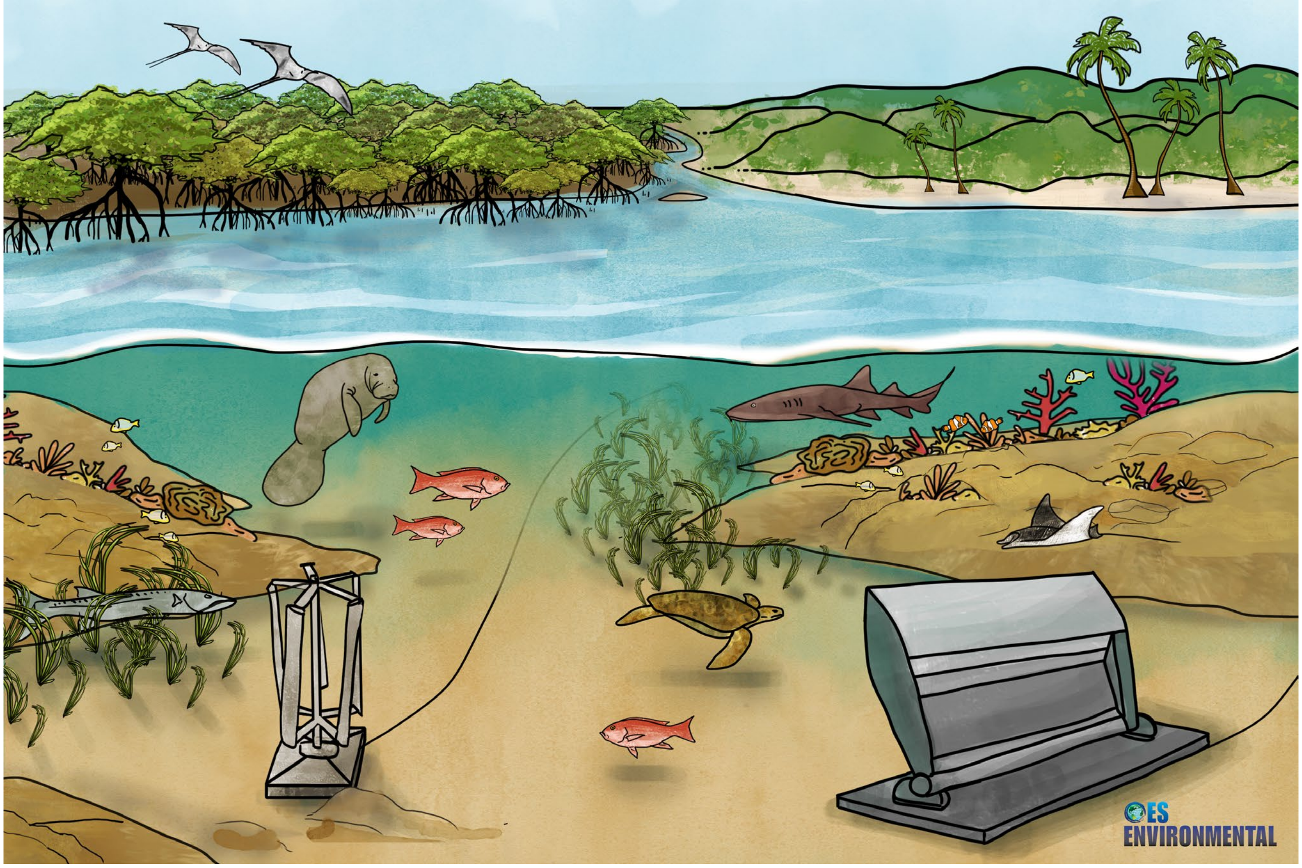

Figure 10.2. Schematic of a tidal turbine and a wave energy converter in a tropical marine ecosystem. (Illustration by Stephanie King)

10.1.
STRESSOR-RECEPTOR INTERACTIONS IN TROPICAL AND SUBTROPICAL ECOSYSTEMS

The potential environmental effects of MRE in tropical and subtropical regions can be described through specific stressor-receptor interactions, and consideration of the unique animals, habitats, and ecosystem processes present. These interactions can differ depending on the MRE technology considered.

The potential environmental interactions associated with the development of MRE in tropical and subtropical regions are similar to those identified in temperate regions: collision risk, underwater noise, electromagnetic fields, changes in benthic and pelagic habitats, changes in oceanographic systems, entanglement, and displacement (see Chapter 3). These interactions are specifically relevant for wave, tidal, and ocean current energy, except for collision risk which is only relevant for tidal and ocean current energy. The prevalence and perceived importance of these interactions may differ in tropical and subtropical regions, likely due to the unique receptors susceptible to change. Changes in habitat, underwater noise effects on marine life, collisions between tidal or riverine turbine blades and marine animals, and changes in oceanographic systems were identified by the survey participants as the most important interactions to consider in tropical and subtropical regions.

The potential interactions associated with OTEC are similar to those associated with other MRE technologies (e.g., artificial reef effects and other changes in habitat, changes to migratory routes, entanglement, and pathways for invasive species). However, some unique effects associated with OTEC are those related to the cold water return, the release of nutrient-rich water, the entrainment of marine life in deep cold water pipes, and chemical discharges. The cold deep ocean water brought to the surface for heat exchange in the OTEC process must be returned to the ocean. However, this water could be up to 20°C colder than ambient surface water and could potentially shock organisms if discharged at the surface, or destabilize the stratification of ocean water that maintains warm water at the surface (Giraud et al. 2019). To mitigate these effects, the cold water must be discharged at an intermediate depth so that it is rapidly diluted to match ambient temperatures. The cold water pipe, which pumps ocean water from 800-1000 m below sea level or more in most OTEC operations, also has the potential to suck up and entrain fish or other marine organisms, bringing them up to the surface where they are unlikely to survive the change in pressure or temperature (Lamadrid-Rose & Boehlert 1988; Myers et al. 1986). However, evidence from over eight years of operating the Okinawa Prefecture OTEC facility in Japan indicates that this event is extremely rare (i.e., less than one fish seen per year; B. Martin, pers. comm.). Similarly, the Natural Energy Laboratory of Hawaii Authority OTEC facility in the US has never recorded such an event (L. Vega, pers. comm.), suggesting the frequency of an entrainment event will likely remain below detection, even with targeted monitoring programs. Finally, closed OTEC systems use ammonia or other chemicals as the heat exchange medium, and accidental leakage of these chemicals in gaseous form could be harmful to marine life.

Potential effects from salinity gradient energy technologies are not well studied. One theoretical study performed in the Río Lagartos Biosphere, in the Yucatan Peninsula, Mexico, highlighted potential effects from salinity gradient energy technologies, such as changes in flow and nutrient concentrations that could alter natural ecosystems (e.g., mangroves) and threaten keystone species such as the Caribbean flamingo (*Phoenicopterus ruber*) and the Atlantic horseshoe crab (*Limulus polyphemus*) (Wojtarowski et al. 2021). In the absence of representative pilot projects at megawatt scale for salinity gradient energy, Seyfried et al. (2019) assessed potential environmental effects based on analogies with other coastal facilities sharing similar infrastructure or processes, such as desalination plants or wastewater treatment plants. Unique effects from salinity gradient energy technologies were the impingement and entrainment of organisms because of the intake of both high and low salinity waters and the discharge of chemicals. Currently, there are no known established environmental monitoring programs for salinity gradient technologies in tropical and subtropical regions.

10.2.

RECEPTORS OF CONCERN IN TROPICAL AND SUBTROPICAL ECOSYSTEMS

Effects on biodiversity and ecosystem function are commonly identified as the most important concerns for MRE development in tropical and subtropical regions. When examining the environmental effects of MRE in those regions, there is a need to apply an ecosystem approach (see Chapter 9) to consider all species of an ecosystem, as well as their trophic interactions, instead of focusing on a limited number of key species (e.g., sea turtles) (Mumby & Hastings 2008). Several species in tropical and subtropical regions contribute to the high biodiversity of marine ecosystems and are often listed as endangered or threatened (e.g., most species of sea turtles, whales, manta rays, sharks, dolphins, and corals). Consequently, the sensitivity of ecosystems that characterize potential MRE project sites is a common concern in tropical and subtropical regions. For example, in Mexico and Colombia, areas with the greatest MRE resource potentials often overlap with fragile ecosystems. In Brazil, experts expressed concerns around potential effects on coral reef areas during the installation of MRE devices. Coral reef ecosystems are extremely vulnerable and any negative impacts could be potentially irreversible (Cruz et al. 2018; Mumby 2009).

In Latin America, concerns about the effects of underwater noise resulting from pile drilling during the installation of MRE devices on marine mammals have been raised, particularly in Mexico, Chile, and Brazil. In Brazil, such effects of underwater noise have been considered the main potential impact on biodiversity. The significance of this impact makes it one of the most addressed topics in environmental impact assessment (EIA) studies for offshore development in Brazil since whales can become stressed, weakened, and disoriented. Species of concern for MRE development in Brazil include endangered marine mammals (e.g., sperm whale [*Physeter macrocephalus*]), commercially valuable fish species (e.g., southern red snapper [*Lutjanus purpureus*]), many of which are already overexploited or fully exploited, endangered seabirds (e.g., various species of gadfly petrels [*Pterodroma* spp.]), and sea turtles (e.g., leatherback sea turtle [*Dermochelys coriacea]*) (Silva et al. 2022). In the central and northern parts of Chile, there are also concerns about the risk of collision, entanglement, and displacement for seabirds and marine mammals. Marine mammal (e.g., blue whale [*Balaenoptera musculus*]) migration routes might be disrupted by the presence of an array of MRE devices, potentially leading to displacement (see Chapter 3).

In Asia, the potential for displacement of marine animals was also mentioned by the experts. For instance, in Indonesia, a proposed tidal energy project has raised concerns about the seasonal displacement of vulnerable species, such as the ocean sunfish (*Mola mola*). Concerns have also been raised in the Maldives that cetaceans and whale sharks could be displaced from their migration routes. Other concerns around the environmental effects of MRE in Asia are related to effects on coral reefs and tropical marine life, and are associated with changes in habitat, particularly in Indonesia, Vietnam, and Singapore (e.g., changes to fish communities). For tidal projects in the Philippines, effects on coral reefs are less of a concern as developments would be in high velocity current areas with benthic habitat dominated by rocks, algae, and soft coral colonies. Sensitive areas in the Philippines are generally well described and could be suitably avoided when selecting a deployment site.

In Hawaii, experts highlighted that protected and endangered species are the main concern related to potential environmental effects of MRE, particularly related to the risk of entanglement and underwater noise for sea turtles (e.g., hawksbill turtle [*Eretmochelys imbricata*]), Hawaiian monk seals (*Monachus schauinslandi*), and whales (e.g., humpback whale [*Megaptera novaeangliae*]).

In Australia, experts primarily expressed environmental concerns about the effects on benthic communities, fish (e.g., artificial reef effect), and ecosystem processes. Negative impacts on seagrass beds have been observed associated with the mooring of an MRE device. Certain projects have decided to schedule the deployment of their device during the austral summer as they are less likely to have negative impacts on marine mammals due to collision risks; although these deployments could be constrained with cyclone and monsoon seasons.

Beyond the concerns related to environmental effects, the effects of MRE on tropical and subtropical ecosystems could directly influence the services they provide to society and impact socioeconomic systems.

10.3.
SOCIOECONOMIC CONCERNS IN TROPICAL AND SUBTROPICAL ECOSYSTEMS

In tropical and subtropical regions, MRE development may have significant socioeconomic effects on nearby coastal and island communities if their needs are not considered during the project planning phase (Borges Posterari & Waseda 2022). These coastal and island communities are often small and isolated, and often rely on expensive diesel fuels for electricity generation or do not have access to reliable electricity (Pandyaswargo et al. 2020). The transition to, or adoption of renewable energy sources has been a recent focus in several tropical and subtropical regions, with an emphasis on social acceptance and economic impacts of MRE (Adesanya et al. 2020; Fadzil et al. 2022; Ramachandran et al. 2021).

As it is often the case with new renewable energy projects, coastal residents may be worried about impacts on local communities and tourism and may not accept MRE projects along their coastlines due to impacts to viewshed or existing uses of the ocean (Hubbard 2009). However, residents may express these issues in terms of environmental concerns instead, often as a result of lack of information, or lack of access to available information regarding the potential environmental effects of MRE. Coastal communities are keen observers of new project developments in their marine space and often participate in development processes, so their social perceptions play a crucial role as their influence can expedite, slow down, or stop projects (also see Chapter 5). Engaging with stakeholders regularly and from an early stage of the MRE project is crucial to assure public support. In Indonesia, public support for a tidal energy project at Larantuka Strait started to rise once the public was aware of the benefits of the project (Ramachandran et al. 2020). The tidal energy project would provide electricity in a region without reliable energy infrastructure, which would positively influence the local community.

More than in temperate areas, coastal communities in tropical and subtropical regions rely heavily on nearshore fisheries to support their economies. For example, the Lafkenche law in Chile, passed in 2008, provides exclusive access rights to coastal areas and resources to Indigenous communities (González-Poblete et al. 2020). A need for new policies has been expressed in Chile to allow the co-existence of artisanal fisheries and MRE, based on potential interactions of MRE devices and their supporting infrastructure with the fisheries. In Vietnam, there is concern that MRE projects could cause negative impacts on the fishing communities' livelihood. Fisheries are also of major importance in Japan and the government will only enable leasing for MRE if an agreement is reached between fishers and MRE developers. Such agreement is developed in consultation with local fishing associations.

The economy in tropical and subtropical countries is often dependent on tourism, and potential conflicts with MRE development could occur (e.g., wave energy developments in key coastal areas popular for surf tourism) (Borges Posterari & Waseda 2022; Fadzil et al. 2022). For example, in Indonesia, the potential displacement of the ocean sunfish associated with the presence of a tidal energy project could result in a reduced number of scuba divers who come from all over the world to observe this species. In Australia, visual impacts of MRE devices are also perceived as impactful to tourism. MRE projects can be halted easily due to negative public perceptions and community opinions if seen as a risk to fishing and tourism activities in vulnerable coastal communities.

Small islands and isolated coastal territories encounter challenges in ensuring reliable access to energy, freshwater, and food while pursuing sustainable development. The imperative to fulfill these needs, coupled with the imperative to address climate change through mitigation and adaptation efforts, has prompted the development of renewable energy systems. A comprehensive solution tailored to the unique requirements of those territories is the concept of an Ocean Technology Ecopark (Osorio et al. 2016). Such a concept could comprise an OTEC plant, diverse applications for deep ocean water use, and a dedicated research and development center. An Ocean Technology Ecopark has been proposed on San Andres Island (Colombia) for implementing OTEC technology, water desalination, and establishing a viable business model for deep ocean water use.

10.4.

CASE STUDIES

This section overviews case studies of MRE development in tropical and subtropical regions, aiming to highlight distinctive environmental considerations and associated socioeconomic concerns within these ecosystems. The case studies were selected based on available information about environmental effects of MRE.

WAVE ENERGY IN THE UNITED STATES

The wave energy potential in Hawaii is the highest globally because of the presence of four primary wave types with trade wind waves especially providing a consistent energy resource within the state (Stopa et al. 2011). The island of O'ahu was chosen as the ideal place for a development of a wave energy test site because of its access to the windward direction in Kaneohe Bay (north coast of O'ahu), exposure to the trade wind waves, its access to population centers, and the availability of a shallow shelf (Stopa et al. 2013) (Figure 10.3).

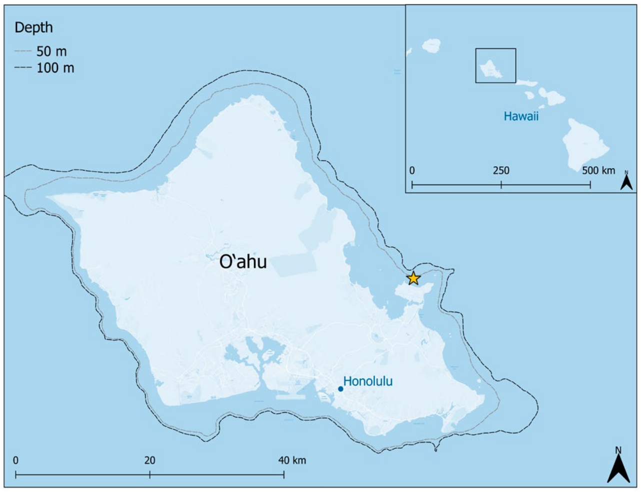

Figure 10.3. Map of the United States Navy Wave Energy Test Site (WETS; yellow star) off the island of O'ahu, Hawaii.

The US Navy Wave Energy Test Site (WETS) has been in operation since 2004 and was the country's first grid-connected wave energy test site. The site includes three test berths at different water depths (30 m, 60 m, and 80 m) and hosts developers to test their pre-commercial wave energy converter (WEC) devices in an operational setting.

Several wave energy devices have been tested at WETS through the years and field monitoring has been conducted to study the potential environmental effects of those devices (Cross et al. 2015; Polagye et al. 2017). Within O'ahu, Kaneohe Bay has a complex estuarine system with a large barrier coral reef, numerous patch reefs, fringing reefs, and several riverine inputs (Aeby 2007; Hunter & Evans 1995). This complex system provides a habitat for numerous species, including those listed on the US Endangered Species Act (ESA) (e.g., scalloped hammerhead sharks [*Sphyrna lewini*]). Types of environmental monitoring that have been considered or conducted at WETS include:

- Acoustic measurements (e.g., active sweeping sonars for monitoring marine mammals and schools of fish);
- Sediment transport measurement/observations at WEC moorings;
- Protected marine species monitoring (e.g., optical and acoustic sensors for active and passive tracking of marine life);
- Water chemistry; and
- Electromagnetic fields.

Ongoing surveys and project/device specific monitoring have been taking place at the site since 2003 with little to no interactions observed with ESA listed species near the site, and no impacts highlighted within reports on ESA-listed species. There was only one sighting of two green turtles (*Chelonia mydas*) in 2019 within the site, but no impacts were recorded. Outside of ESA listed species, the interactions at WETS have been minimal for cetaceans and the site itself has created an artificial reef setting for corals and invertebrates with very little impact on the species. Fish have also benefitted from this artificial reef and the biomass of fish (e.g., bluestripe snapper [*Lutjanus kasmira*]) has been increasing.

TIDAL ENERGY IN AUSTRALIA

Australia is surrounded by great MRE resources, especially waves along the west coast and tidal in the northwest. Clarence Strait, near Darwin in the Northern Territory, was the focus of a tidal energy project and a planned tidal test center (Clarence Strait Tidal Energy Project and Tropical Tidal Test Center) (Franklyn 2008), although now abandoned (Figure 10.4). The strait is located on the Sahul Shelf in the Indo-West Pacific region, between Timor and the Arafura Seas. In the middle of Clarence Strait lies the Vernon Islands group, surrounded by deep channels with strong and complex tidal currents.

Figure 10.4. Map of the tidal energy project and tropical tidal test center (yellow star) in Clarence Strait, Australia.

The northwest continental shelf of Australia presents a rich biodiversity that can be classified into multiple coastal mesoscale bioregions, with its northern region considered part of the "realm of reef-building corals" (Wilson 2013). The Vernon Islands are an important species-rich coral reef and mangrove system, home to an endemic anemone fish (Tiwi Land Council 2013). Surrounding waters are critical habitats for dugongs and sea turtles because of the seagrass and algal beds around the islands. Numerous fish species of recreational value are found in the waters of Clarence Strait, including barracuda, tuna, and golden snapper (*Lutjanus johnii*). In addition, all waters and coastline around Clarence Strait hold cultural values to local First Nations people. Because of these biodiversity and cultural riches, the area has been declared a Conservation Reserve. An Environmental Impact Statement (EIS) was required for the Clarence Strait project to move forward because of numerous concerns due to the knowledge gaps around the environmental effects of tidal energy on tropical ecosystems and the presence of vulnerable species and habitats. Issues of particular concern included:

- Potential impacts on coral reef communities;
- Risks to rare and threatened species and listed migratory species occurring in the impact area;
- Changes to feeding grounds for sea turtle and dugong, with cultural importance;
- Potential impacts on seabed and water quality; and
- Potential impacts on traditional, recreational, and commercial use of the area.

The EIS required baseline assessments of marine vertebrates including mammals, marine benthic invertebrates, terrestrial fauna and flora, physical environment, and socioeconomic aspects (human dimension) (Table 10.1), as well as post-installation monitoring. Literature reviews on potential physical interactions of marine mammals with tidal turbines, as well as acoustic interferences and impacts of turbine noise, were conducted (Franklyn 2008). However, the project was later canceled.

Table 10.1. Baseline assessment requirements for the Clarence Strait tidal energy project and tropical tidal test center in Australia.

Receptors	Baseline assessment requirements
Marine vertebrates	• Extent and behavior of vertebrate marine species in and around project area
Marine mammals	• Assess physical interaction risk of tidal turbines • Understand acoustic interference and impact of device noise
Invertebrates	• Impacts of cables on benthic habitat
Terrestrial fauna and flora	• Describe and map native terrestrial and inter-tidal flora and fauna
Physical environment	• Bathymetry of turbine site and cable route to identify any seabed features of significance • Impacts of gravity base on seabed • Water quality of marine waters and spatiotemporal variations • Maps of regional distribution of species’ suitable habitat and of habitat areas to be disturbed • Soil/sediment types and land units within the onshore project footprint
Human dimensions	• Describe floral and faunal species and biological communities of local, regional, and national significance • Describe the existing and projected maritime traffic use • Describe the isolated danger or safety zones required to mark and protect project assets • Identify archaeological/heritage artifacts of importance and vulnerability of features identified • Understand cultural impacts • Detail all chemicals to be stored and/or used on site

TIDAL ENERGY IN THE BAHAMAS

The Bahamas is a country consisting of more than 700 islands, cays, and islets of which only 28 are populated. Like many island countries, the Bahamas almost entirely relies on imported fossil fuels, leaving it vulnerable to global price fluctuations that directly impact the cost of electricity and contribute to climate change. The Bahamas, with a vast coastline and access to ocean currents, could potentially explore tidal energy as a renewable energy source (Bethel et al. 2021), especially devices operating at less energetic flows (Encarnacion et al. 2019; Kaddoura et al. 2020). However, the specific suitability of tidal energy in the Bahamas would require detailed assessments and studies on:

- **Tidal currents:** Examining the local tidal current patterns, including the amplitude (tidal range) and frequency of tides, is crucial. Areas with larger tidal ranges typically offer more significant energy potential.
- **Coastal geography:** The Bahamas’ coastal geography needs to be assessed, including the presence of suitable locations for tidal energy devices and cable landfalls to connect to local power grids.
- **Environmental impact:** Conducting EIAs is essential to understand the potential effects of tidal energy projects on marine ecosystems, including fish and other aquatic life.
- **Infrastructure:** The availability of infrastructure, such as electrical grids and transmission lines, is vital for connecting tidal energy generation facilities to the electricity grid.
- **Economic viability:** Analyzing the cost-effectiveness of tidal energy projects and considering government incentives and policies for renewable energy development is crucial.

The Sharktunes project in the Bahamas aimed to study the response of large predatory fish to underwater noise from tidal energy devices to assess potential effects on, and if necessary, mitigation approaches to, these ecologically important species. This project is led by Uppsala University, Octopus Ink Research & Analysis, Chalmers University of Technology, and Swedish University of Agricultural Sciences. The tidal energy device studied for this project was the Minesto tidal kite. The underwater noise emitted from the tidal energy device included low frequency components which may hypothetically attract (or repel) species such as sharks and other large marine predators. All playbacks used in the study were broadcasted at realistic levels for a tidal kite, by far lower than those known to cause direct physiological injury for nearby individuals of fish or marine mammal species (U.S. Department of Commerce 2018). Two underwater noise profiles were emitted with an underwater speaker during a four-week field campaign in several locations in the vicinity of Cape Eleuthera (west side of Eleuthera), on the west side of the Bahamas (Figures 10.5, 10.6). The two noise profiles corresponded to the noise emitted by a prototype-size tidal kite (small tidal kite) and a full-scale tidal kite (big tidal kite). Shark behavior was recorded with stereo video cameras facing in two directions (two cameras vertically down, two cameras horizontally). Playbacks were emitted for 15 minutes and included sound profiles known to attract sharks (e.g., low frequency pulsed sound and helicopter sound), and sound profiles known to be a deterrent (e.g., sound of distant lightning strikes) (Chapuis et al. 2019).

As of 2024, the project is ongoing and final analyses remain to be completed. Preliminary results showed that Caribbean reef shark (*Carcharhinus perezii*), nurse shark (*Ginglymostoma cirratum*), bull shark (*Carcharhinus leu-*

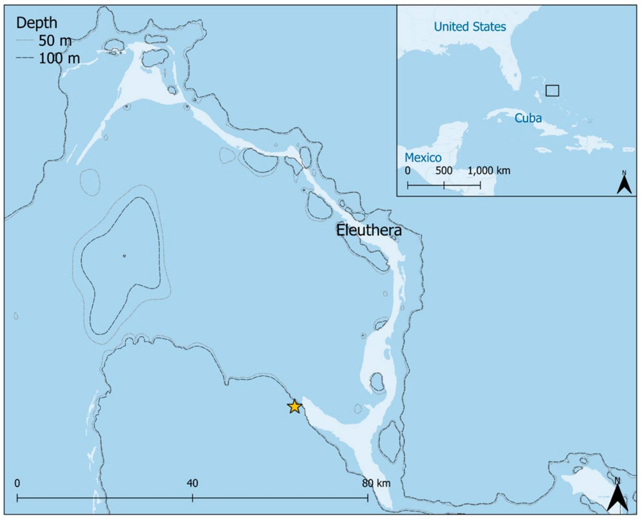

Figure 10.5. Map of the Sharktunes project location (yellow star) in Eleuthera, the Bahamas.

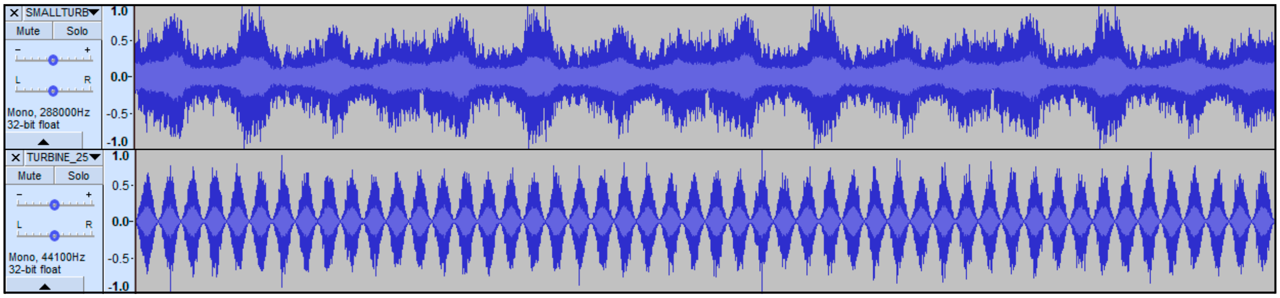

Figure 10.6. Noise profiles emitted in the marine environment using an underwater speaker to study the behavior of sharks in the Bahamas. Two noise profiles were used, corresponding to those emitted by a small tidal kite (top) and a big tidal kite (bottom).

cas), and great hammerhead shark (*Sphyrna mokarran*) were present during the field campaign (Figure 10.7). Caribbean reef, nurse, and bull sharks were not attracted to noise similar to a tidal kite, but seemed to avoid it, although habituation seemed to occur over time. Unlike the other species, bull sharks seemed attracted to the low frequency pulse noise, although the attractiveness of the noise dissipated with time, probably due to habituation. Finally, sudden loud noise startled the sharks, but the effect wore off rapidly. From these preliminary results, underwater noise effects from a tidal kite on sharks are likely low, but more studies are needed to better understand shark behavior around a real device.

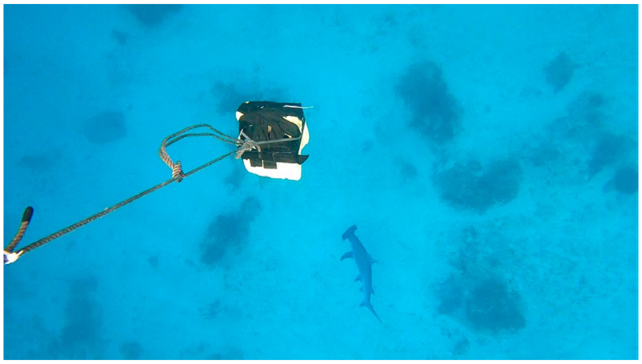

Figure 10.7. Picture of a great hammerhead shark swimming under the stereo video camera during recording.

OTEC IN MEXICO

Mexico is located on the border of two biogeographic regions (Nearctic and Neotropical), which contributes to the existence of a variety of climates and ecosystems, providing Mexico with great biodiversity (Koleff et al. 2018). Its long coastline and access to the Caribbean Sea, Gulf of Mexico, and Pacific Ocean provide heterogeneous conditions that offer a variety of marine resources for MRE exploitation (Hernández-Fontes et al. 2019).

Because of Mexico's great biodiversity, natural areas have been protected and zoning programs established by the National Commission for Natural Protected Areas for the protection of representative ecosystems, flora and fauna, natural resources, and environmental services, where extractive activities are restricted. Therefore, government and federal organizations must be involved in the development of any MRE projects, particularly during stakeholder engagement, as many of these protected areas are located along the coastline and co-occur with potential MRE sites (Hernández-Fontes et al. 2019), some of which are biodiversity hotspots (MacGregor-Fors et al. 2022; Myers et al. 2000). Although there have been few MRE projects off Mexico, research on the environmental interactions suggests potential effects on coastal habitats, such as mangroves, seagrass beds, and coastal lagoons, and on marine animals, such as sea turtles, migratory birds, endangered/threatened species (mostly marine mammals), and endemic fish species (Carrera Chan et al. 2020; Marin-Coria et al. 2021; Rivera et al. 2020; Wojtarowski et al. 2021).

Among the various MRE resources present off Mexico, OTEC has high potential. Suitable bathymetry and temperature differential for OTEC are found along both the Pacific and Caribbean Sea coastlines (Garduño-Ruiz et al. 2021). Although there are significant OTEC resources off Mexico, environmental concerns have slowed down the development of projects. Environmental effects were investigated at a theoretical location for an open-cycle OTEC plant on the west coast of Cozumel Island, Quintana Roo (Carrera Chan et al. 2020) (Figure 10.8). The significance of relevant environmental effects (positive or negative) and their magnitude associated with the presence of an OTEC plant were assessed. The four most significant negative effects identified were: dragging nutrients to the surface, redistribution of ocean water bodies, impact by organic antifouling chemicals, and brine discharge. OTEC projects could be developed around Cozumel Island if measures to minimize environmental effects are taken, such as avoiding mangrove habitat and protected natural areas. Other MRE technologies such as ocean current turbines are being considered in the region and environmental monitoring is under development.

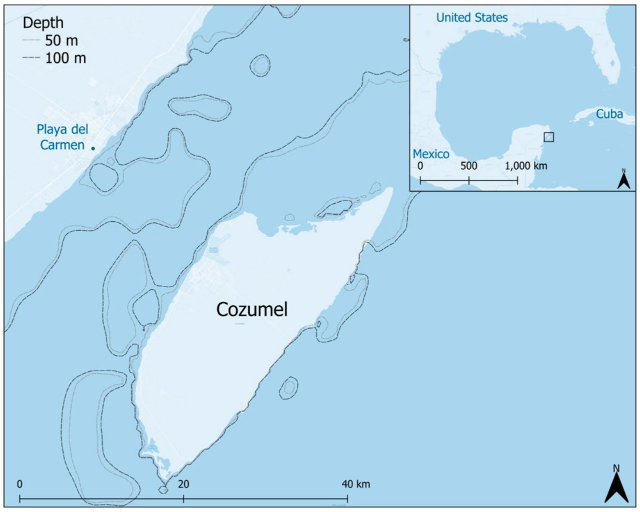

Figure 10.8. Map of Cozumel Island, Mexico.

10.5.
RESEARCH NEEDS AND KNOWLEDGE GAPS

Tropical and subtropical marine ecosystems are composed of diverse habitats and complex ecological interactions spanning from the shoreline to the open ocean (Dahlgren & Marr 2004). These ecosystems face unprecedented anthropogenic threats and are vulnerable to environmental variations (Kenchington & Hutchings 2018). All countries considered to be megadiverse are in the tropical zone and there is a clear overlap between these biodiversity hotspots and MRE resources (Felix et al. 2019). These characteristics make tropical and subtropical ecosystems highly sensitive and increase their vulnerability to the cumulative effects of anthropogenic activities at sea, including MRE development.

When considering the development of MRE in these ecosystems, there is a lack of scientific information about the possible environmental effects, as compared to temperate regions. This lack of scientific information is largely due to the scarcity of MRE projects deployed in these regions so far. The slow development of the MRE industry in tropical and subtropical regions is generally linked to the lack of investment from government entities and to environmental and social constraints. Environmental regulations, marine spatial planning, industry roadmaps, guidance for developers, and standardization around EIA of MRE projects are generally lacking. In Latin American countries, there are few environmental or ecosystem characterizations and baseline data available for most of the coastline. Instead, environmental studies are typically conducted locally, are not conducted on a seasonal basis, and often the results are not well disseminated or made publicly available. The lack of long-term baseline data prevents a comprehensive understanding of the natural variations of ecosystems, which is needed to evaluate the potential effects of MRE projects (Mendoza et al. 2019). Similarly in Asia, because of the very early stage of MRE development there, knowledge and expertise about potential environmental effects are very limited and primarily built on other existing coastal and offshore activities such as fishing, aquaculture, and oil and gas. In Japan, the EIA law was implemented in 1999 (Environmental Impact Assessment Act 1997) and is commonly used to assess the environmental effects of diverse offshore activities, but it does not include guidance or laws on MRE.

To better understand the potential effects of MRE development on habitats, species, ecosystems, and communities in tropical and subtropical countries with suitable MRE resources, it is essential to establish and enable early stage projects, around which research and monitoring can be undertaken. This includes single device deployments and where suitable, small arrays. To fill knowledge gaps on the environmental effects of MRE in tropical and subtropical ecosystems, studies need to go beyond the framework of stressor-receptor interactions that is being used in temperate regions. Except for interactions related to OTEC technologies that can only be deployed in tropical and subtropical regions, there are no interactions entirely specific to the tropical and subtropical regions; differences lie in the species and habitats that are potentially impacted. Therefore, considering the whole ecosystem and the linkages between species is key (Hammar & Gullström 2011). To evaluate the potential effects of a salinity gradient energy project in Mexico, Wojtarowski et al. (2021) focused on describing the biogeochemical characteristics of the coastal lagoon ecosystem, the associated mangrove habitat, and the threatened and keystone species inhabiting the ecosystem. This approach enabled researchers to consider the structure and function of the ecosystems and the associated biodiversity (Martínez et al. 2021). Identifying priority and vulnerable habitats as well as monitoring and mitigating the long-term effects on nearby tropical ecosystems and migratory tropical species are key to sustainably advancing the industry. Extreme events (e.g., hurricanes, typhoons, tsunamis) are common in tropical and subtropical regions and their frequency and intensity are increasing with climate change (Balaguru et al. 2023; Cha et al. 2020); adapting MRE technologies to the environment and these extreme events is needed.

Social perception also plays a crucial role across tropical and subtropical regions and can either enable or hinder the development of MRE projects (Martinez & Komendantova 2020; Ramachandran et al. 2020). Coastal and island communities are observant and participative and can strongly influence the ultimate success or failure of a project. Project slowdowns or cancellations can happen either as a result of insufficient information on potential interactions of such projects with the surrounding environment or due to a negative perception of these industries in general (e.g., Clarence Strait tidal energy project in Australia). Social issues are heterogeneous within a country and a better understanding of concerns and potential social effects within a specific region is needed. The lack of knowledge on local social concerns would benefit from strong community involvement from the inception of an MRE project. Educating stakeholders on MRE in general and environmental and socioeconomic effects in particular will also benefit the MRE industry as awareness and education are key to community acceptance (Bonnevie et al. 2019; Ramachandran et al. 2020). More research is needed to better understand how the energy, financial, and social benefits of MRE can reach the nearby residents and businesses in a specific region (Hernández-Fontes et al. 2020; Lyons et al. 2023).

10.6.
RECOMMENDATIONS

While access to research and development funding is often more limited in tropical and subtropical regions, baseline environmental research will help address many concerns for environmentally protected marine areas that may include endangered or threatened species, coupled with socioeconomic research that will improve understanding of the potential effects on local communities. Several recent studies have combined the investigation of both environmental and social effects to select sites for MRE projects in Mexico for salinity gradients (Wojtarowski et al. 2021), wave energy, current energy, and OTEC (Hernández-Fontes et al. 2020); and in China (Zhang et al. 2019) and Colombia (Osorio et al. 2016) for OTEC.

Recommendations for advancing the knowledge of the environmental effects of MRE in tropical and subtropical ecosystems include the following:

- Establishing collaborations and partnerships between industry, government, academia, and communities, to enable research around early stage MRE projects;
- Establishing a list of priority research questions on a regional or national basis;
- Combining monitoring and modeling studies to understand the natural variations of the environment;
- Applying a system-level effects approach to assess the cumulative effects of MRE with other anthropogenic activities at sea; and
- Establishing clear pathways for data transfer and knowledge sharing from projects in other parts of the world, including opportunities for technology transfer where appropriate.

10.7.
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