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Assessing the Potential of Marine Renewable Energy in Mexico: Socioeconomic Needs, Energy Potential, Environmental Concerns, and Social Perception

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Abstract: Although the literature on Sustainable Development Goals (SDGs) is vast worldwide, studies in Mexico focusing on Marine Renewable Energy (MRE) and SDGs are only beginning to emerge. Despite this academic gap, Mexico has signed up for the United Nations SDGs, which include producing clean and affordable energy and reducing CO_2 emissions to slow global warming. The country is, therefore, committed to implementing measures to help achieve these goals. This study is the first multidisciplinary analysis performed at a national level in Mexico, aimed at identifying sites for efficient Marine Renewable Energy (MRE) production while considering socioeconomic needs, environmental risks, and societal acceptance of the new technologies. We first calculated the energy potential from nearshore winds, waves, marine currents, and offshore thermal gradients. The results show that electricity needs are greater in the 11 states where levels of marginalization are highest. The production of MRE is feasible in three of these regions. However, because Mexico is home to significant natural coastal ecosystems and protected species, care is necessary to produce electricity while protecting Mexico's megadiversity. Social perception of the use of MRE is variable: the inhabitants of some locations are willing to accept the new technologies, whereas those in others are not. MRE production in Mexico is feasible but will face environmental and social issues that must be addressed before deploying new devices in the oceans.

Keywords: marine energy potential; wave energy; current energy; OTEC; wind energy; environmental concerns; biodiversity; social perception

1. Introduction

Two of the 17 Sustainable Development Goals (SDGs) of the United Nations mention energy production. These refer to the need to produce affordable and clean energy (goal number 7) and to slow down global warming by reducing CO_2 emissions (goal number 13, Climate Action) (https://sdgs.un.org/goals, accessed on 14 May 2024). Indeed, the relevance of the SDGs is evident in the scientific literature, which shows a 14% increase in the number of studies over the last 4.5 years, reaching nearly 30,000 publications [1]. According to the literature review of these authors, most studies (nearly 6000) address goal 13 (Climate Action), and the majority of them were performed in only a handful of countries. The contribution of Latin American countries to the literature on SDGs is small [1]. Nevertheless, according to WoS, Mexico ranks 30 worldwide, with 448 studies dealing with SDGs, 20% of which mention "Energy" in their titles, and 16% mentioning "Climate Change" (WoS consulted 2 August 2024).

Mexico has signed up for this international agreement and is committed to implementing measures to help achieve the SDGs. The actions necessary to reduce and substitute the use of fossil energy fuels include clean and renewable energy production. In this sense, in 2017, the Mexican Secretariat of Energy [2,3] stated that national electricity production should be 35% renewable by 2024 and 50% by 2050. One possible source for generating electric power is Marine Renewable Energy (MRE), which includes tides, currents, waves, thermal and salinity gradients, and offshore winds [4].

New MRE technology for ocean energy harvesting is being developed worldwide, including in Mexico. The number of MRE devices being tested has substantially increased [5,6], and the number of those deployed is expected to rise in the future [4]. Importantly, as new technologies develop, it is necessary to determine and monitor the environmental impacts of MRE so that these are kept at a minimum [7–9]. Furthermore, it is necessary to reduce any other associated risks and uncertainties.

In addition to the above, evidence shows that ignoring societal perception and acceptance of these new technologies is an error. They must also be considered before such new technologies are deployed [10–12]. Previous experience has demonstrated that it will likely fail when local inhabitants oppose a nearby project. For example, González and Estévez [13] described wind turbine developments in southern Spain. They stated that even when politicians, industry, and environmental organizations find themselves allied in favor of a renewable energy project, the community affected and small conservation groups may forcefully oppose the installation of devices. That is, opposition to a renewable energy project may occur even when the economic conditions are very favorable and where there are minimal effects on the biota, the landscape, the archeological wealth, noise, or traditional economic activities. Therefore, assessing the community's perception of new technologies, such as MRE, is necessary before deploying devices.

The Mexican coast holds real potential for MRE to meet the nation's electricity demands, as the shoreline is long, over 11,000 km, ranking it 15th worldwide. Furthermore, there is still a significant need for electricity in many settlements near the coast of Mexico (see, for example, [14–17]). Thus, this study aimed to assess and find, at a country-wide level, (a) the need for electricity in coastal settlements lacking such provision; (b) the potential of MRE production, through nearshore wind, waves, ocean currents, and thermal gradients; (c) the location of critical coastal ecosystems, protected species, and biodiversity hotspots (Protected Natural Areas); and (d) the perception of local inhabitants and key social actors towards the deployment and functioning of MRE devices in specific areas. Finally, we performed a qualitative analysis to identify locations where harvesting MRE for electricity production would be most beneficial, considering socioeconomic needs, energy potential, environmental restrictions, and social perception.

Because our work involved different types of information, a combination of approaches was used. Socioeconomic needs and environmental restrictions were analyzed using public databases (see Table S1). The power potential was calculated using numerical modeling and public databases. This study was designed as exploratory and, therefore, followed an inductive approach. That is, we explored the possibilities of using MRE along the coasts of Mexico to search for patterns and predictions that could later be tested in a deductive manner to confirm or reject subsequent hypotheses. Thus, we looked for geographical patterns related to MRE and their coincidence with the socioeconomic needs of local populations and biodiversity hotspots. We also explored the societal acceptance of the new energy harvesting devices in three locations where deployment is considered.

2. Materials and Methods

2.1. Definition of Coast

Because we studied coastal human settlements and ecosystems, a clear definition of the coast was necessary. Many definitions of "coast" are used in the literature (see, for example, [18,19]) and The Millennium Ecosystem Assessment [20]. Nevertheless, for practical reasons, in this study, the terrestrial coast was considered as an area < 100 m above sea level and <10 km from the shoreline inland. Offshore, the coast was defined as an area up to 200 m in depth, and the photic zone included the subtidal and pelagic zones.

2.2. Socioeconomic Attributes and Electricity Needs in Mexico

Several databases were used to describe the socioeconomic attributes and to determine electricity needs in coastal populations. First, socioeconomic variables (such as population size and level of socioeconomic marginality) were gathered from the National Institute of Statistics and Geography (INEGI, in Spanish) database. Then, locations lacking electricity were identified based on public databases from the Federal Commission of Electricity (CFE, in Spanish).

We used the CEM 3.0 model (Continuous Elevations Model) from INEGI to map coastal areas according to the definition of coast provided above. Then, we located geographically all the human settlements lacking electricity in Mexico according to the CFE database (Advances in Electrification), which lists the human settlements lacking electricity along with their latitudes and longitudes. The geographical coordinates were obtained from the 2010 Population and Housing Census (INEGI). For each locality, a unique code of 7 characters was assigned (2 to indicate the Mexican state, 3 for the municipality, and 4 for each locality). Finally, each location was superimposed onto the elevation layer of the GIS, and thus, we generated the map of coastal human settlements lacking electricity in Mexico.

2.3. Theoretical Marine Energy Potential

The marine energy potential in Mexico was determined by the median (Q2, or second quartile) of the theoretical potential for waves, wind, and ocean currents and the technical potential for thermal gradient, using Ocean Thermal Energy Conversion (OTEC). The median was chosen as the representative statistical parameter to refer to the energy potential at the power value below which 50% of the data fall. This represents the minimum amount of available energy that would be present 50% of the time, providing a threshold associated with the duration a device can generate a certain energy level. Using the median also avoids distortion from extreme values, which can occur when using the mean.

2.3.1. Wave and Wind Energy

The medians of the wave (P_{wave} in kW/m, Equation (1)) and wind power (P_{wind} in kW/m^2, Equation (2)) were calculated along the Mexican coast to characterize these energy sources potential using the following equations:

$$P_{wave} = \frac{\rho g^2}{64\pi} T_p {H_s}^2 \tag{1}$$

$$P_{wind} = \frac{1}{2}\rho_{air} V^3 \tag{2}$$

where g is gravity (9.81 m/s^2), ρ is the average density of seawater (1025 kg/m^3), H_s is the significant wave height in m, T_p is the wave peak period (s), ρ_{air} is the average density of air (1.225 kg/m^3), and V is the 10 m wind velocity (m/s). The wave and wind parameters along the Mexican coastline (H_s, T_p, and V) were obtained from the climate reanalysis ERA5 [21], which combines satellite and field weather observations with climate models to generate a comprehensive dataset. We computed hourly data from 1940 to 2022 from this dataset in a 0.5° × 0.5° grid; the nearest grid points to the coastline were selected for this analysis.

2.3.2. Ocean Current Energy

The median of the power from ocean currents ($P_{current}$ in W/m^2, Equation (3)) was used to characterize the energy potential of ocean currents along the Mexican coast:

$$P_{current} = \frac{1}{2}\rho w^3 \tag{3}$$

where ρ is the average density of seawater (1025 kg/m^3), u is the east current velocity component (m/s), v is the north current velocity component (m/s), and w is the current velocity modulus (m/s, Equation (4)).

$$\boldsymbol{w} = \sqrt{\boldsymbol{u}^2 + \boldsymbol{v}^2} \tag{4}$$

The velocity components were obtained from Martínez et al. [4] along with the Regional Ocean Modelling System (ROMS), which uses the hydrostatic and Boussinesq approximations to solve the Reynolds Averaged Navier Stokes Equations in three dimensions [22], for the 10 km strip of land, measured from the shoreline. The bathymetry was obtained from GEBCO (General Bathymetric Chart of the Oceans), a comprehensive bathymetric dataset for the world's oceans [23]. For more details on the ROMS implementation, see Martínez et al. [4].

2.3.3. Thermal Gradient Energy

The thermal gradient energy potential was characterized by the median of the OTEC net power (P_{net} in MW). The time series for the OTEC net power, which depends on a minimum difference of 20 °C between the sea surface temperature and the deep ocean temperature, was obtained from Martínez et al. [4] using the equation proposed by [24] (Equation (5)) for daily thermal differences, from 2002 to 2012, along the Mexican coast.

$$P_{net} = Q_{cw}\frac{3\rho C_p \varepsilon_{tg}\gamma}{16(1+\gamma)}\frac{(TD)^2}{T} - P_{pump} \tag{5}$$

where Q_{cw} is the volume flow rate of the deep seawater intake at 1000 m depth (138.6 m^3/s) [25]; γ is the ratio between the hot- and cold-water flows (1.5); TD is the temperature difference between water at the surface and a depth of 1000 m (°C); T is the absolute temperature of the surface seawater (K); ρ is the average density of seawater (1025 kg/m^3); C_p is the specific enthalpy of seawater (0.004 MJ/kgK); ε_{tg} is the efficiency of the turbogenerator (0.75); and P_{pump} is the pump power (MW, Equation (6)). For more details on the estimation of the TD, see Martínez et al. [4].

$$P_{pump} = Q_{cw}0.30\frac{\rho C_p \varepsilon_{tg}\gamma}{4(1+\gamma)} \tag{6}$$

2.4. Environmental Concerns

The assessment of potential environmental restrictions was based on the location of relevant coastal biodiversity hotspots (protected natural areas), which host sites with a relatively high number of endemic and protected species. We also included coastal ecosystems (coral reefs, seagrass beds, and mangroves) and some protected species under the Mexican Official Standard NOM-059-SEMARNAT-2010 (marine mammals, marine turtles, horseshoe crabs, and the pink snail) [26]. The literature considers these species vulnerable to environmental disturbances, such as deploying MRE devices [4,27–29]. Additionally, horseshoe crabs and pink snails have commercial value and are relevant because they help sustain ecosystem functioning [30,31].

The maps of protected natural areas in Mexico were created based on the shape file elaborated by the National Commission of Protected Natural Areas (May 2021), which is publicly available at CONANP (http://sig.conanp.gob.mx/website/pagsig/info_shape.

htm, accessed on 23 February 2024). Then, we calculated the closest distance from these areas to the coast, considering the continental shoreline from the map of State Political Division 1:250,000 [32], using a Lambert Conformal Conic projection. Finally, maps with the distribution of coastal ecosystems and protected species were created based on public information available from the Mexican government.

2.5. Social Perception of MRE

These studies aimed to explore local people's acceptance or opposition to the new technologies by pondering the potential benefits to society and the direct and indirect changes in their cultural and environmental conditions. These studies used direct interactions with the inhabitants and took place in only three locations, where it was determined previously that it was possible to harvest MRE [17,33]. The studies took place in El Cuyo (Yucatán), Cozumel (Quintana Roo), and La Paz (Baja California Sur) (Table 1). The type of MRE available varied between sites, as did the attributes and socioeconomic conditions of the populations.

Table 1. Human settlements where societal perceptions towards MRE were explored. The number of inhabitants, type of potential MRE, methods used to evaluate social perception, and number of interviewees are provided for each settlement.

Settlement	State	Inhabitants	Type of MRE	Method Used to Assess Social Perception	Number of Interviewees
El Cuyo	Yucatán	1567	Salinity gradient/offshore wind	Semi-structured interviews with adults and high school students; workshop and human figure drawing with primary school children [33].	12 semi-structured interviews, 32 students from primary school
Cozumel	Quintana Roo	86,415	Ocean current	Questionnaire applied to local inhabitants. Likert scale and open interviews with key stakeholders [17,33].	50 inhabitants
La Paz	Baja California Sur	798,447	Ocean current	Questionnaire applied to local residents, Likert scale (this study).	77 adults

Different approaches were followed, and they were chosen following the socio-cultural attributes of each settlement. For example, in El Cuyo, a small settlement with a low level of education, many people only attended primary school. In this case, the best method was a semi-structured interview, where the interviewees could freely express themselves without needing prior knowledge of the questions. We thus performed semi-structured interviews with residents, including adult men and women and younger high school students. We also employed inquiry techniques via a socio-environmental education workshop and used human figure drawing with primary school pupils.

On the other hand, the mean level of formal education in Cozumel is higher than in El Cuyo (high school). Thus, a Likert scale questionnaire was considered more suitable because it assesses the population's knowledge of MRE. These questionnaires were applied to the adult resident population. In addition, we conducted open interviews with key local actors to seek decision maker's perceptions.

Finally, the population's education level in La Paz is like Cozumel, so we again applied a Likert scale questionnaire to the city's adult residents. The results of the social perception studies in El Cuyo and Cozumel have been previously reported [17,33]. In the case of La Paz, this is the first time these results have been published.

Independently of the methods used, all participants were fully informed and guaranteed that their responses would remain anonymous and that their private personal information would not be shared. Before the interviews, we ensured that all the participants understood the study's goals by providing sufficient information regarding MRE devices. All agreed to have their responses published. We closely followed the Mexican laws regarding the ethics of studies with humans: the "Ethics Code of the Public Administration" (https://www.dof.gob.mx/nota_detalle.php?codigo=5642176&fecha=08/02/2022#gsc.tab=0, accessed on 1 January 2024) and the General Law of private information (https://www.gob.mx/indesol/documentos/ley-general-de-proteccion-de-datos-personales-en-posesion-de-sujetos-obligados, accessed on 1 January 2024). Similarly, the institutional Ethics Committee of INECOL verified that the study was performed respectfully, honestly, and without discrimination or harassment (http://www1.inecol.edu.mx/cv/CV_pdf/etica/codigos_conductaeticareglas_integridad.PDF, accessed on 1 January 2024).

3. Results

3.1. Socioeconomic Attributes and Electricity Needs in Mexico

3.1.1. Socioeconomic Marginality

The spatial distribution of marginality in coastal areas in Mexico varies (Figure 1). The states on the Mexican Pacific coast showed the highest marginality values. In general, marginality tends to be low or very low in states in the northwest (except for Baja California) and the Gulf of Mexico. In turn, marginality is relatively high in states in the South Pacific. The Mexican Caribbean is heterogeneous, with very low and very high marginality.

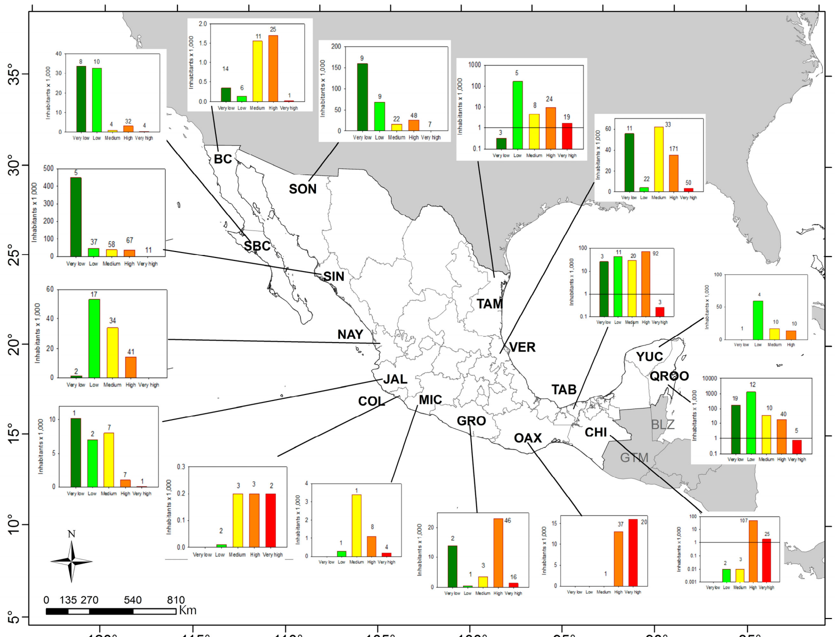

Figure 1. Spatial distribution of marginality along Mexican coasts (<10 km from the shoreline and <100 m above sea level). Green represents low marginality, and red represents very high marginality. Yellow and orange indicate moderate marginality. The plots have different scales along the Y-axis because of differences in the number of settlements and inhabitants.

3.1.2. Coastal Settlements with and without Electricity

The need for grid electricity is found throughout the country (Figure 2): more than 46,000 settlements and 200,000 inhabitants do not have electricity supplied through the electricity grid. The coasts follow a similar trend to the rest of the country. Across Mexico, there are some 10,000 settlements less than 10 km from the shoreline and less than 100 m above sea level; eleven million people live in these settlements (Table 2). Here, there are 183 settlements without electricity (Figure 2 and Table 2), 2% of all coastal settlements, meaning around 6000 inhabitants (less than 1%). While this is a small percentage, the quality of life of these people who lack electricity is woeful and needs urgent attention. The electricity needs through the grid are especially noticeable along the Gulf of Mexico, the Mexican Caribbean, the southern tip of the Baja California Peninsula, and the southeastern Pacific coast (Figure 2).

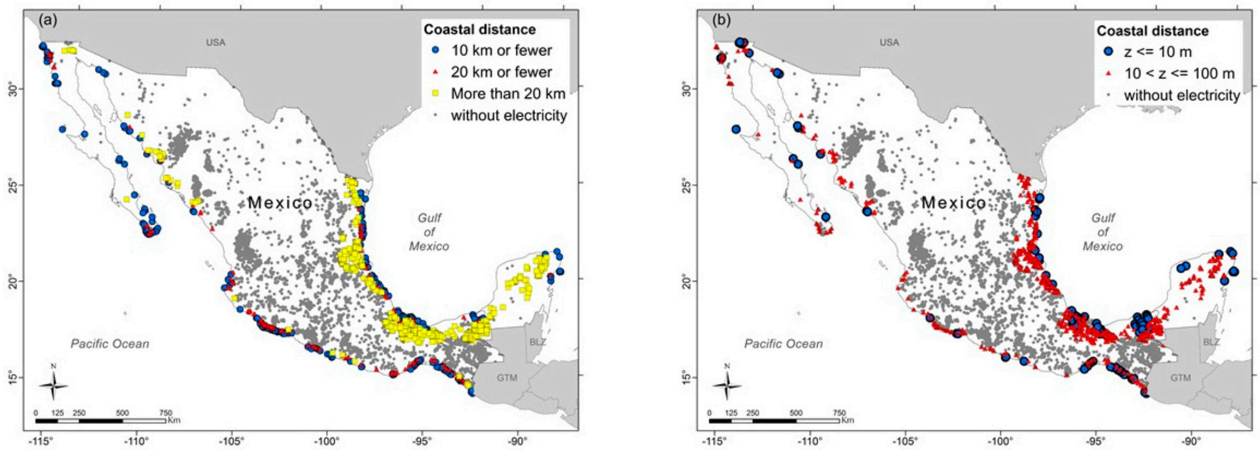

Figure 2. Geographical distribution of coastal settlements lacking electricity in Mexico: (**a**) coastal settlements, based on the distance to the coast; (**b**) coastal settlements, based on altitude from sea level.

Table 2. Mexico's coastal settlements and inhabitants without electricity are at different altitudes and distances from the coast. Data from [32,34] (% from total in each definition of coast; masl = meters above sea level).

Altitude/Distance from the Coast	Total Inhabitants	Inhabitants Lacking Electricity (%)	Number of Settlements	Number of Settlements Lacking Electricity (%)
<10 masl	6,963,698	5862 (0.084)	7932	153 (1.93)
<100 masl	26,872,370	22,623 (0.084)	46,064	796 (1.73)
<10 km from the shoreline	11,669,381	6822 (0.058)	11,396	225 (1.97)
<100 masl and <10 km from the shoreline	11,327,488	6000 (0.053)	10,399	183 (1.76)

3.2. Theoretical Marine Energy Potential

The four marine energy sources' median power (Q2) varies across the country's coasts (Figure 3). The results of waves, wind, and current energy correspond to the total theoretical amounts of electricity generated but not necessarily the amount of energy that is technically and ecologically feasible to harvest. The potential for OTEC technology is shown for thermal gradient energy.

The regions with the highest wave power, 12 and 22 kW/m, were found in the Mexican Pacific (Figure 3a). Figure 3b shows that the highest median (Q2) wind power values are on the southern part of the Pacific coast, at around 0.25 kW/m^2, in the Isthmus of Tehuantepec. The Yucatan Peninsula also has high potential, at around 0.20 kW/m^2. The highest potential for ocean currents (Figure 3c) was found north of the Yucatan Peninsula (state of Quintana Roo) on the Mexican Caribbean. The annual median OTEC net power is shown in Figure 3d, where the highest potentials are found off the southern Pacific coast (e.g., off Puerto Angel, Oaxaca, the 1000 m isobath, the pink line in Figure 3d, is 3.9 km from the coast) and on the Caribbean coast (e.g., in Cozumel, Quintana Roo, the 1000 m isobath is 5.4 km from the coast). These conditions make the extraction of deep ocean water technically feasible. In Figure 3, coastlines with no colored data mean that the theoretical power's median (Q2) value is below the selected thresholds, as shown in the legend of each panel.

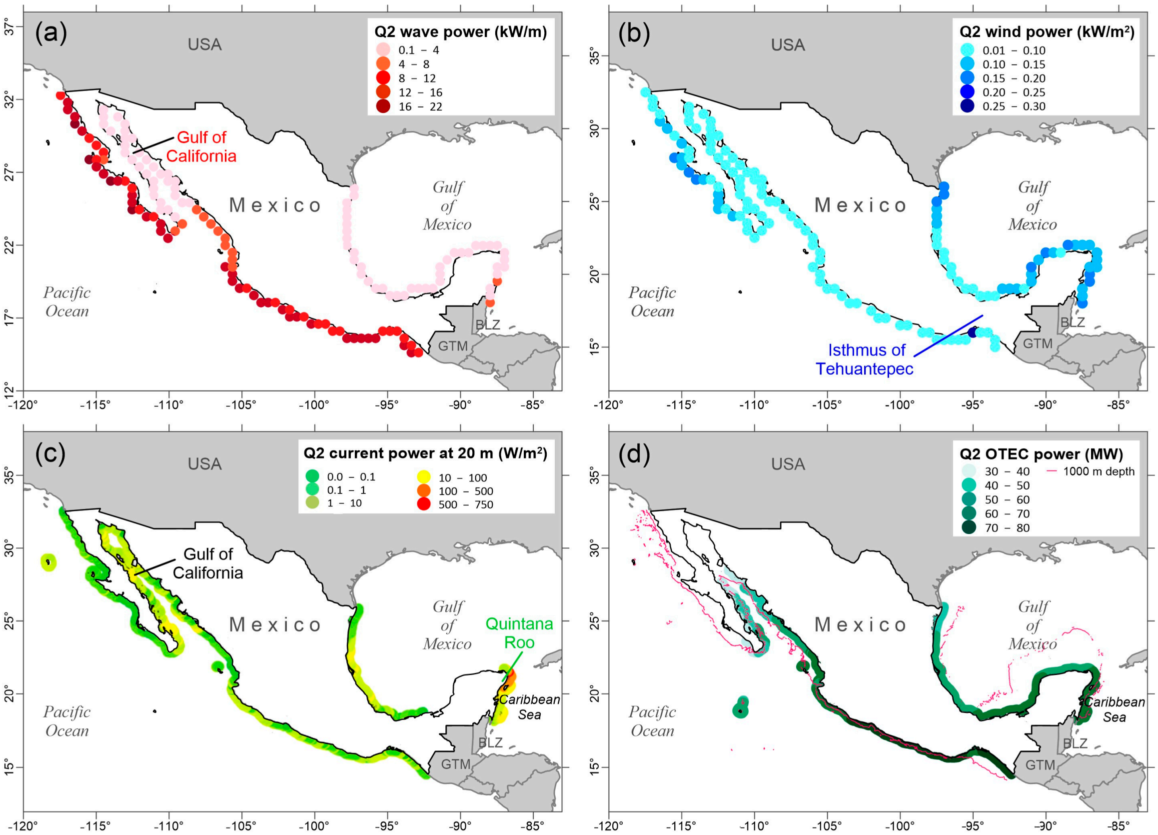

Figure 3. Median (Q2) power potential: (**a**) wave, (**b**) wind, (**c**) ocean current, and (**d**) OTEC.

3.3. Environmental Restrictions

Protected natural areas in Mexico are subject to specific regulations for protecting, conserving, and restoring their natural ecosystems [35]. Human activities have not significantly altered these areas and include high biodiversity hotspots. Currently, Mexico has 182 Protected Natural Areas where biodiversity conservation is paramount, covering over 90 million hectares. Of these, 37 are marine and coastal, totaling 649,587 km^2. Furthermore, 92% of the islands of Mexico are within these protected areas (Figure 4). Thirty-seven terrestrial and 31 marine protected natural areas are located near or at the coast or less than 20 km from the shoreline (Figure 4).

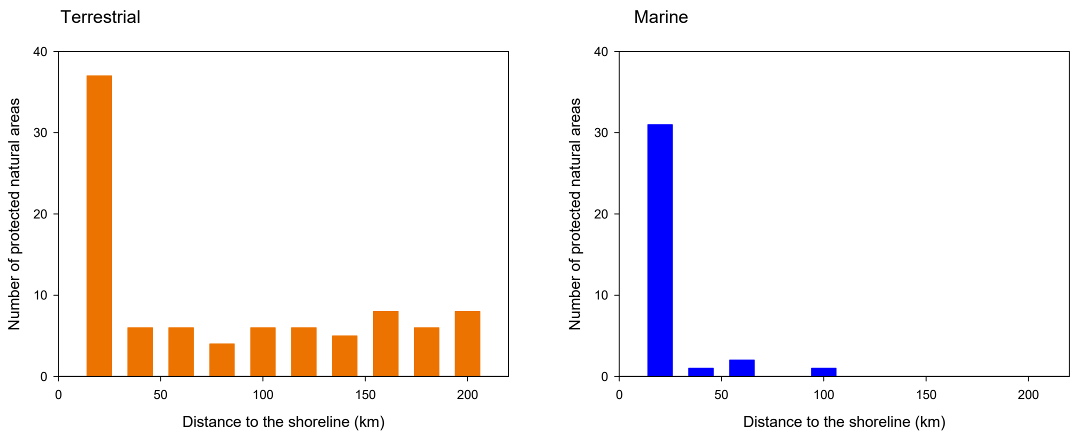

Figure 4. The number of protected natural areas in Mexico includes terrestrial and marine ecosystems (information from the National Commission of Protected Natural Areas—CONANP). Distances were measured from the shore, inland (terrestrial), and seaward for marine ecosystems.

Various natural ecosystems exist on the Mexican coasts, such as the Mesoamerican Reef System (MARS) in the Mexican Caribbean, seagrass beds, and mangroves (Figure 5). These ecosystems host significant biodiversity and act as nurseries for many marine species.

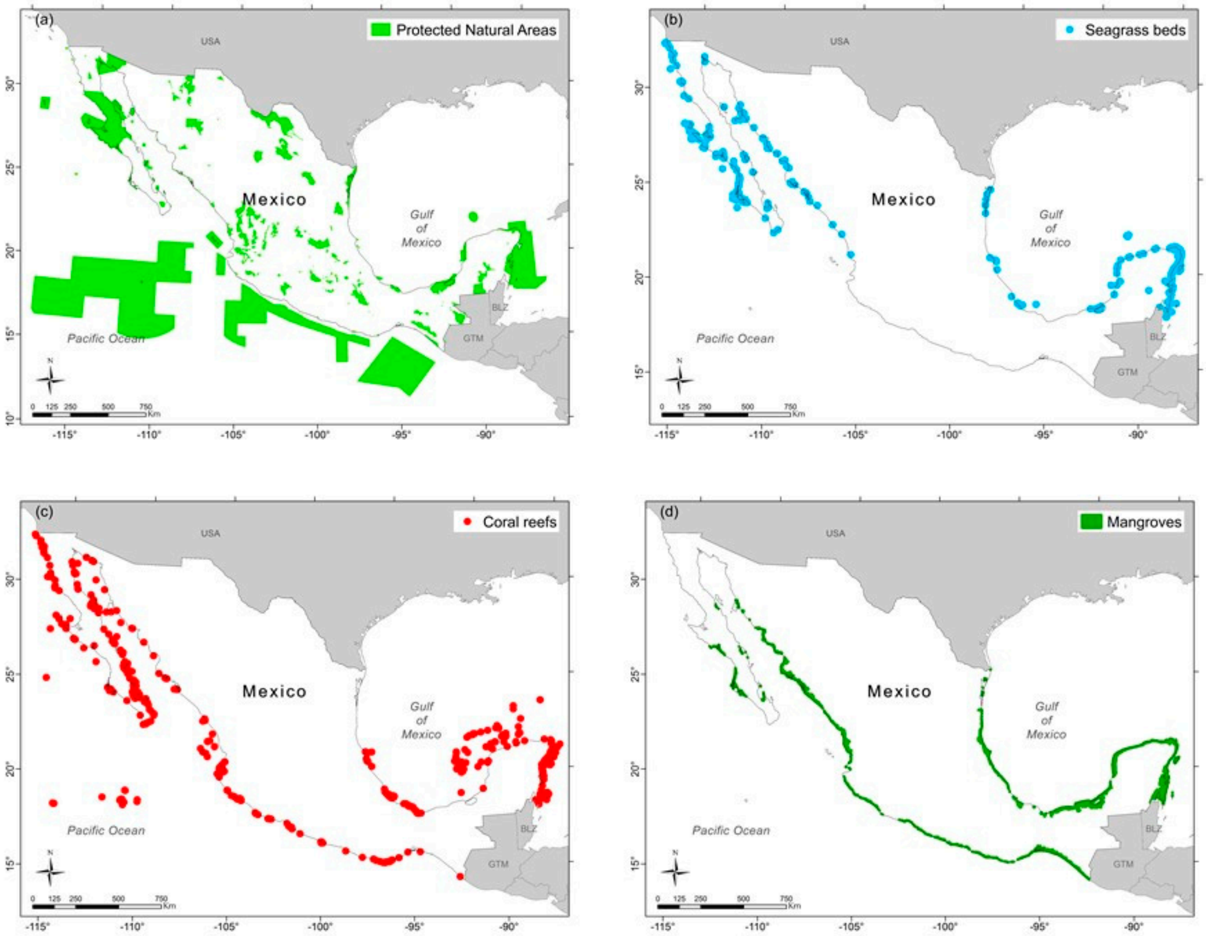

Figure 5. National distribution in Mexico of (**a**) protected natural areas and coastal ecosystems, (**b**) seagrass beds, (**c**) coral reefs, and (**d**) mangroves.

Finally, the Mexican coasts host many protected species, such as marine mammals and marine turtles (Figure 6). Two threatened invertebrates (the horseshoe crab and pink snail) live exclusively on the coasts of the Yucatan peninsula (Figure 6).

Overall, there are 90 marine species protected by Mexican laws: 18 invertebrates, 42 mammals, 17 fish, 7 reptiles, 4 plants [36], and 42 marine mammals [37]. The oceanographic region with the highest species richness is the Gulf of California (34 species), followed by the North Pacific (33), South Pacific (32), Caribbean Sea (24), and the Gulf of Mexico (17) [37–39] (Figure 6a). Mexican law protects all marine mammals under the Mexican Official Standard norm NOM-059-SEMARNAT-2010 [26] (Table 3). These categories differ from the International Union for Conservation of Nature (IUCN) Red List but are comparable. Several species are of particular concern. The vaquita porpoise is the most relevant because it is endemic to a minimal area in the northern Gulf of California, and there are very few (around 10 individuals) [40]. Therefore, the species is classified as critically endangered (CR) by the IUCN and endangered (P) by NOM-059 (Table 3). In the North Pacific, several species are categorized as endangered (P in NOM-059): the North Pacific Right whale, the Guadalupe fur seal, and the southern sea otter. The threatened northern elephant seal (A in NOM-059) also inhabits this region. In the Gulf of Mexico and the Caribbean Sea, the endangered (P) Caribbean manatee is of high conservation concern (Table 2). Several whale species (grey, blue, and humpback whales) use the west coast of the Baja California peninsula as a migratory corridor. Thus, special care is necessary before installing and running MRE plants in these regions. Mexican laws protect marine mammals, even though they are not considered endangered. The Rice's whale occupies a limited area in the northeastern Gulf of Mexico (U.S. waters), and there have been visual and acoustic locations of the species in that area [41]. However, there are no confirmed sightings of this whale, or its closest relative, in the Exclusive Economic Zone of Mexico, according to the most complete and up-to-date revision (1952–2018) of cetacean sightings in Mexican waters [41].

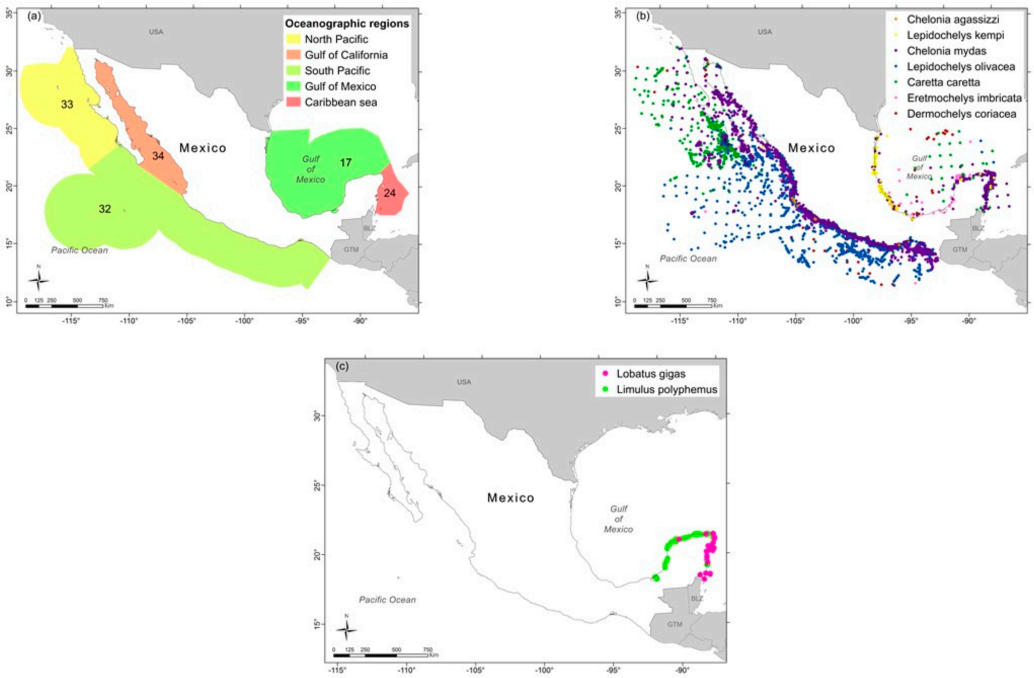

Figure 6. Spatial distribution of sites with Mexican (**a**) marine mammals (number of species in the oceanographic regions), (**b**) seven marine turtles, and (**c**) horseshoe crab (*Limulus polyphemus*) and pink snail (*Lobatus gigas*).

Regarding marine turtles, Mexico is internationally recognized for its importance to sea turtles. Six of the seven species in the world live off the coasts of Mexico. In fact, due to the abundance of nesting areas of various marine turtle species, several of the beaches most important for turtles in the world are found in Mexico. According to international and national assessments, all species of sea turtles are at risk. In Mexico, they are classified as endangered species by the Mexican Official Norm NOM-059-SEMARNAT-2010. Marine turtles are also on the Red List of the International Union for the Conservation of Nature (IUCN). All species are distributed along both coasts of the country [42]. The following descriptions of the distribution and conservation status of the Mexican marine turtles are based on the report by the National Commission of Protected Natural Areas [42]. The leatherback turtle (*Dermochelys coriacea*) is the largest marine turtle in the world and is found mainly along the southern Pacific coasts of Mexico. It is critically endangered because its populations are extremely reduced. In turn, the olive sea turtle (*Lepidochelys olivacea*) nests along the southern Mexican Pacific and is considered vulnerable, with its population slowly increasing. The green sea turtle (*Chelonia midas*) and the hawksbill turtle (*Eretmochelys imbricata*) are found on all Mexican coasts. It is endangered, but its populations are slowly increasing. Kemp's Ridley Turtle (*Lepidochelys kempii*) is the smallest marine turtle endemic to the Gulf of Mexico. It is also critically endangered, and its populations are extremely reduced. Finally, the marine loggerhead turtle (*Caretta caretta*) is mainly found along the coasts of the Yucatan Peninsula, and it is vulnerable to extinction, although it has relatively stable populations.

Table 3. Distribution of marine mammal species in Mexican waters by oceanographic region (Figure 6). Conservation status is according to the International Union for Conservation of Nature (IUCN) Red List (https://www.iucnredlist.org/, accessed on 14 February 2023) and the Mexican list of species at risk [26,43]. Red List categories: DD (Data Deficient), LC (Least Concern), NT (Near Threatened), VU (Vulnerable), EN (Endangered), CR (Critically Endangered. NOM-059 categories: Pr (Sujeto a Protección Especial = Under Special Protection), A (Amenazada = Threatened), P (En Peligro de Extinción = Endangered), NM = not mentioned.

Family	Common Name	Scientific Name	Oceanographic Regions					Status	
			North Pacific	Gulf of California	South Pacific	Gulf of Mexico	Caribbean Sea	IUCN	NOM-059
Order Cetartiodactyla									
Mysticeti									
Balaenidae	North Pacific right whale	*Eubalaena japonica*	X		X			EN	P
Eschrichtiidae	Gray whale	*Eschrichtius robustus*	X	X	X			LC	Pr
Balanopteridae	Minke whale	*Balaenoptera acutorostrata*	X	X	X		X	LC	Pr
	Sei whale	*Balaenoptera borealis*	X	X	X		X	EN	Pr
	Bryde's whale	*Balaenoptera edeni*	X	X	X		X	LC	Pr
	Blue whale	*Balaenoptera musculus*	X	X	X			EN	Pr
	Fin whale	*Balaenoptera physalus*	X	X	X	X		VU	Pr
	Humpback whale	*Megaptera novaeangliae*	X	X	X	X	X	LC	Pr
Odontoceti									
Physeteridae	Sperm whale	*Physeter macrocephalus*	X	X	X	X	X	VU	Pr
Kogiidae	Pigmy sperm whale	*Kogia breviceps*	X	X	X	X	X	LC	Pr
	Dwarf sperm whale	*Kogia sima*		X	X	X	X	LC	Pr
Ziphiidae	Baird's beaked whale	*Berardius bairdii*	X	X	X			LC	Pr
	Longman's beaked whale	*Indopacetus pacificus*	X	X	X			LC	NM
	Hubbs' beaked whale	*Mesoplodon carlhubbsi*	X					DD	NM
	Blainville's beaked whale	*Mesoplodon densirostris*	X	X	X			LC	Pr
	Gervais' beaked whale	*Mesoplodon europaeus*				X	X	LC	Pr
	Ginkgo-toothed beaked whale	*Mesoplodon ginkgodens*	X	X	X			DD	Pr
	Pigmy beaked whale	*Mesoplodon peruvianus*	X	X	X			LC	Pr
	Cuvier's beaked whale	*Ziphius cavirostris*	X	X	X		X	LC	Pr
Delphinidae	Common dolphin	*Delphinus delphis*	X	X	X		X	LC	Pr
	Pigmy killer whale	*Feresa attenuata*		X	X	X	X	LC	Pr
	Short-finned pilot whale	*Globicephala macrorhynchus*	X	X	X	X	X	LC	Pr
	Risso's dolphin	*Grampus griseus*	X	X	X	X	X	LC	Pr
	Fraser's dolphin	*Lagenodelphis hosei*	X	X	X	X	X	LC	Pr
	Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	X	X	X			LC	Pr
	Northern right whale dolphin	*Lissodelphis borealis*	X					LC	Pr
	Orca	*Orcinus orca*	X	X	X		X	DD	Pr
	Melon-headed whale	*Peponocephala electra*		X	X		X	LC	Pr

Table 3. *Cont.*

Family	Common Name	Scientific Name	Oceanographic Regions					Status	
			North Pacific	Gulf of California	South Pacific	Gulf of Mexico	Caribbean Sea	IUCN	NOM-059
	False killer whale	*Pseudorca crassidens*	X	X	X	X	X	NT	Pr
	Pantropical spotted dolphin	*Stenella attenuata*		X	X	X	X	LC	Pr
	Clymene dolphin	*Stenella clymene*				X	X	LC	Pr
	Striped dolphin	*Stenella coeruleoalba*	X	X	X			LC	Pr
	Atlantic spotted dolphin	*Stenella frontalis*				X	X	LC	Pr
	Spinner dolphin	*Stenella longirostris*		X	X	X	X	LC	Pr
	Rough-toothed dolphin	*Steno bredanensis*		X	X		X	LC	Pr
	Bottlenose dolphin	*Tursiops truncatus*	X	X	X	X	X	LC	Pr
Phocoenidae	Dall's porpoise	*Phocoenoides dalli*	X					LC	Pr
	Vaquita	*Phocoena sinus*		X				CR	P
Order Sirenia									
Trichechidae	West Indian manatee	*Trichechus manatus manatus*				X	X	EN	P
Order Carnivora Pinnipedia									
Otariidae	Guadalupe fur seal	*Arctocephalus philippii townsendi*	X	X				LC	P
	California sea lion	*Zalophus californianus*	X	X	X			LC	Pr
Phocidae	Northern elephant seal	*Mirounga angustirostris*	X	X				LC	A
	North Pacific harbor seal	*Phoca vitulina richardii*	X					LC	Pr
Mustelidae	Southern sea otter	*Enhydra lutris nereis*	X					EN	P
Total species			33	34	32	17	24		

In addition to the above, it is pertinent to acknowledge briefly other endangered marine species found along Mexican coasts. Endangered fish include the great hammerhead shark (*Sphyrna mokarran*), the seahorse (*Hippocampus* sp.), and some mantas and rays, such as the giant manta ray (*Mobula birostris*) [43]. Indeed, the pink snail (*Lobatus gigas*) and the horseshoe crab (*Limulus poliphemus*) are among the most critically endangered invertebrates due to predatory overexploitation for pharmaceutical and ornamental reasons, respectively. For this reason, we focused on these species in this study.

It is important to reaffirm that this study did not aim to perform an in-depth analysis of the conservation status of coastal and marine species in Mexico. Instead, we focused on some of the most relevant and iconic examples to help assess the environmental concerns associated with the deployment and functioning of marine renewable devices.

3.4. Social Perception of MRE

The social perception of renewable energy varied in the locations where this was assessed (Table 4). In El Cuyo, knowledge of renewable energy was generally limited. The interviewees had not heard of MRE harvesting, only solar energy. Most people were averse to environmental changes and did not consider these new technologies environmentally appropriate.

Table 4. Social perception towards MRE in three Mexican locations where the deployment of MRE devices would be feasible.

Location	Knowledge of MRE	Accept the Deployment of MRE Devices	It Is Possible to Harvest Electricity from the Ocean	MRE Devices Are Good for the Environment	Reference
El Cuyo	Yes: women (50%), men (70%), teenagers (80%) (only solar energy)	Yes: men (67%), women (33%), teenagers (50%)	Limited knowledge of RE	Generally reluctant to change the landscape: women 67%, teenagers 25%	[33]
Cozumel	Yes 65% (MRE included)	Yes 88%	Yes (44%); Neutral (56%)	Yes 64%	[33]
La Paz	Yes 65% (MRE included)	Yes 97%	Yes (72%)	Yes 86%	

The perception of people towards renewable energy was more favorable in Cozumel and La Paz, where renewable energy was known to more than half the interviewees in both locations. Most were willing to accept deploying renewable energy devices in their localities. Furthermore, those interviewed in Cozumel and La Paz were aware of the possibility of harvesting electricity from the ocean and considered that these new technologies were environmentally appropriate. However, in Cozumel, there are signs of resistance to projects developed by outsiders. Consequently, it would be necessary to implement an efficient communication, interaction, and local participation strategy before installing MRE devices here. In brief, deploying MRE devices would be socially accepted in Cozumel and La Paz but not in El Cuyo.

4. Discussion

According to D'Adamo et al. [1], only some studies focus on one or several SDGs in Latin America. However, the number of studies dealing with this topic in Mexico is relatively significant compared to other countries in the region. Nevertheless, within the list of publications that mention the SDGs in Mexico, only Rivera et al. [44] focus specifically on MRE. Indeed, studies dealing with MRE (whether these are framed explicitly within the SDGs or not) are scarce in the country.

The current study is the first to focus on the different types of MRE with a multidisciplinary approach at the national level in Mexico. As the analysis had a broad scope, the study provides an overview of potential MRE harvesting sites across Mexico. It addresses the deficits of electricity provision in coastal areas at the national level and considers social perceptions and environmental concerns.

Given the electricity shortage in many small communities across Mexico, decisive actions are necessary to shift toward renewable energy generation in the country. Mexico's commitment to attaining UN Sustainable Development Goals 7 and 13 on clean and affordable energy and reducing CO_2 emissions to slow global warming must be taken seriously. However, at the same time, we must also improve the living conditions of those Mexicans who lack electricity.

The ultimate goal of this study was to find potential sites for efficient MRE production that are both socioeconomically favorable and environmentally acceptable so that Mexico can contribute to global sustainability.

4.1. Electricity Needs in Mexico and Theoretical Energy Potential

Our findings show a substantial need for electricity in many coastal settlements. The results also show that the calculated energy that could be harvested means that MRE is a viable alternative for coastal settlements, especially for those less than 10 km from the coast and at less than 100 masl. The most promising MRE regions are the Mexican Caribbean, the southeastern Pacific, and Baja California. While these three regions have been previously identified as potential sites, most work has focused only on energy availability and technical feasibility at different spatial scales (e.g., for wave energy, [45,46]). In contrast, environmental concerns and societal perceptions are generally ignored.

Working at a national scale, the theoretical potential for the various MRE sources presented in this study is a coarse analysis of the spatial variations and does not consider temporal variations. In particular, the numerical modeling to accurately represent the transformation of waves from intermediate to shallow depths induced by wave shoaling, refraction, diffraction, reflection, and breaking requires detailed topo-bathymetric information, which for Mexico does not exist in many regions, and great computational resources are required. Regardless of the implications of this type of modeling, it is impossible to adequately represent the areas of wave concentration or divergence at the scale used in this work. The same is true for harnessing wind resources on the coast.

Different studies have analyzed these variations in more detail for specific sites. However, this work aims to present a general overview (at the national level) of the harvesting potential of these resources and integrate socio-environmental aspects rather than a detailed framework of the availability of the resources for selecting a specific site or technology. The GIS analyses enabled us, on a preliminary basis, to determine where to harvest one or several energy sources simultaneously. Indeed, such information should also consider specific studies to minimize environmental concerns and optimize social benefits.

Finally, finding space, including marine areas, is increasingly challenging. Consequently, an increasingly sought alternative is the development of eco-parks that harvest several energy sources simultaneously and generate a variety of products (e.g., electricity, fresh water, and mariculture). However, these studies are very much site-dependent.

4.2. Environmental Concerns

Although scarce, a few studies [2,14,33] have used environmental and socioeconomic criteria when exploring the technical feasibility of MRE in Mexico. For example, at a local scale, Hernández-Fontes et al. [14] studied the wave, current, and thermal gradient power potential in Michoacan, Mexico. However, they analyzed the environmental concerns using only one legal instrument: Mexico's Natural Protected Areas. Similar simplifications for environmental evaluation exist in a study [17] at a regional scale, which focused on the wave, marine currents, and thermal gradient resources in the Mexican Caribbean, and by [2], who studied potential OTEC sites in Mexico. Other studies [33] explored the environmental concerns regarding MRE and determined potential species and ecosystems that MRE devices could impact. However, no direct studies on the environmental impact of MRE exist in Mexico. They are currently underway.

Because Mexico is a mega-diverse country, the biodiversity found in its coastal areas is very high. Such biodiversity is essential when addressing and mitigating any potentially damaging effects from the deployment and functioning of MRE devices. Protected coastal ecosystems (seagrass beds, coral reefs, mangroves) and species (marine mammals, marine turtles throughout the country, and the horseshoe crab and pink snail in the Caribbean) require special care. Unfortunately, most of these ecosystems and species are understudied because of reduced funding and a lack of qualified personnel.

The literature suggests that MRE devices will likely affect these species [4,47,48]. There is concern regarding potential injuries to marine mammals and other vertebrates from collisions, but no scientific data have reported this. In Mexico, studies in this regard have yet to be undertaken, though one is currently being conducted (unpublished data). Other concerns relate to alterations to migratory routes, disturbances in the benthic environment, and the creation of new habitats [4,47,48]. Nevertheless, empirical evidence of this effect could be more robust; field observations and experimental data are needed, as well as assessments of the intensity of potential effects. Recommendations can more accurately mitigate environmental changes based on such specific observations.

4.3. Social Perception

The social perception towards MRE varied between the three study areas. In El Cuyo, the people's appreciation of their natural heritage contributes to their resistance to new technologies that could alter their territory. The inhabitants mentioned that they should defend their natural heritage, which supports their most relevant economic activities, such as fishing and low-intensity tourism, which are central to their economy. This resistance to change may also be associated with the watchful character played out here historically, since pre-Hispanic times [49]. Activities and constructions that imply a landscape transformation may need to be better received by the people of El Cuyo [33].

Regarding the island of Cozumel, the interviews showed a positive perception of alternative energies and an interest in their use. However, other relevant social challenges exist. In the past, the people of Cozumel opposed projects developed by outsiders (including one for wind energy) [50]. This opposition was associated with the perception that the participation of local agents was ignored and that there had been a lack of communication with the locals regarding the projects. Disinformation and concern about potential environmental impacts further increased social mistrust [33,47]. In conclusion, while the people interviewed in Cozumel have a positive perception of marine energy, it is essential to approach the inhabitants directly and openly, correcting errors made in planning previous projects.

Finally, in La Paz, our results show that those interviewed in the locality are receptive and positive towards developing a marine energy project. Overall, the population is informed and open to changes in their area. In La Paz, there is also concern about the high cost of electricity and the need to care for the environment. Here, it would be appropriate to highlight information on the cost of electricity for homes and the specific environmental impacts of new technologies before the installation of MRE projects.

4.4. Where Are the Best Locations to Deploy MRE in Mexico?

Our results show that the MRE sites with the most potential in Mexico are the Mexican Caribbean, the southeastern Pacific, and the Baja California regions. Here, electricity needs and societal acceptance coincide, but these areas also have high biodiversity. Laws protect the endangered and endemic species found at these sites, prohibiting environmental changes that could threaten protected species and ecosystems [26,51]. For example, mangroves, coral reefs, marine mammals, and turtles live along most of Mexico's coasts. The above means that, environmentally, MRE projects would not be considered appropriate at any of the sites mentioned above. So, while these sites are generally not suitable, on a national or more regional level, locations for deploying MRE devices could be found if we had more detailed and fine-scale information regarding the occurrence and abundance of ecosystems and species. Therefore, after the national diagnostic of this study, more exhaustive, local studies supported by empirical data on the environmental impacts on species and ecosystems are needed. This information would help to identify locations for MRE harvesting that would be technically feasible, socially accepted, and environmentally adequate.

Finally, if comprehensive studies do not show negative environmental impacts on ecosystems or endangered, endemic, or protected species, MREs could provide compensation to protect mangroves, coral reefs, seagrasses, and their protected species. Furthermore, where MRE has the approval of local inhabitants, these projects could prevent the development of other land or marine uses with more negative effects and could, thus, help protect the local biodiversity [47].

4.5. Caveats and Relevance of the Study

The potential impact of MRE on biodiversity was explored using a broad, generalized approach that considered the occurrence of Protected Natural Areas near or at the coast, keystone coastal ecosystems, and several endangered species from Mexican coasts. Ideally, specific information and in-depth analyses regarding the environmental impacts that the deployment of MRE devices may have on local species and ecosystems are required. Unfortunately, work to provide such data is very incipient in Mexico and needs further development. Therefore, in this study, we could only explore environmental concerns (ecosystems and endangered species) that need detailed studies in the future.

We found that Protected Natural Areas, seagrass beds, coral reefs, marine mammals, horseshoe crabs, and pink snails coincided with areas with more potential for MRE production. However, marine turtles mostly coincided with OTEC sites, and no clear patterns occurred regarding mangroves. Again, further, more detailed, site-specific studies are necessary to validate the general trends observed.

The geographical scope of this study was vast, so it is impossible to determine the social acceptance of MRE in all Mexican coastal settlements. These settlements are both abundant and highly diverse. Instead, we focused on a few locations, chosen because the deployment of MRE devices is technically feasible there and to reflect the contrasting socioeconomic backgrounds they have. As expected, the responses and acceptance levels of MRE were varied. The above does not mean the results are invalid or impossible to compare because the methods used differed. As explained above, different methods were deemed necessary because of the characteristics of each settlement. Because the questions asked, by whatever means, were similar, the comparison of perceptions was possible. In brief, the analyses of perceptions showed the variability of opinions and the need to perform such studies on a case-by-case basis. The same variability occurs in the natural ecosystems, MRE potential, and socioeconomic needs. Future studies require a more local, detailed approach to supply accurate, specific data.

Evidence of the relevance and uniqueness of our study can be seen in the study performed by [4]. In their thorough literature review, these authors found 16,432 references focused on at least one of the potential MRE harvesting devices, illustrating the current interest in this topic. Of these, a reduced percentage (17%) dealt with potential environmental impacts, and even fewer (2%) considered societal perception towards the new technologies. These authors do not report any study that includes the three approaches (energy potential, social perception, and environmental concerns).

Finally, several hypotheses, or specific research questions, emerge from this study's results. For instance, what is the correlation between MRE potential and biodiversity? Which are the most efficient MRE devices, and which cause the least environmental damage? How can different MRE harvesting methods be combined? Is societal acceptance of MRE devices correlated with the urbanization and education level of the settlement? What kinds of studies and approaches are helpful to help the stakeholders understand the new technology?

5. Conclusions

Studies on MRE within the framework of SDGs are very scarce in Mexico. The current study is the first to provide a multidisciplinary overview of potential MRE harvesting sites performed at a national level while addressing the deficits of electricity provision in coastal areas and considering social perceptions and environmental concerns. Given the deficit in the electricity supply of many small communities across Mexico, radical actions are necessary, mainly if Mexico is to meet its international pledges to move towards renewable energy generation in a short timeframe. Large-scale MRE projects could significantly improve the lives of those living in coastal communities by providing access to electricity. However, such projects might have negative environmental impacts. On the other hand, small-scale MRE projects (microgeneration) would be more accepted by local communities, promote local technology development, create jobs, and reduce environmental impacts, making these a more sustainable option.

In Mexico, particularly in areas with deep cultural roots and limited economic development, there is a strong perception that new industries do not benefit these communities, which is often true. Therefore, the use of natural resources must be changed to make these communities among the primary beneficiaries; otherwise, the development gap will continue to deepen.

This work suggests new directions for future research to advance with the development and deployment of MRE technology, thus helping Mexico reach the SDGs related to energy and climate action. Indeed, we need to evaluate the best devices for the various types of MRE available in Mexico. It is also necessary to explore the environmental impacts of these modern technologies in detail, using scientific evidence. Finally, communities need to be informed and involved regarding the consequences of the new technologies and the direct socioeconomic benefits and environmental impacts these would have on the settlements involved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16167059/s1, Table S1: References of the databases used to draw the maps with socioeconomic and environmental information.

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