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Is ocean energy an alternative in developing regions? A case study in Michoacan, Mexico

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ABSTRACT

In many parts of the world, renewable energy is being considered as an alternative to supply electricity to communities in developing regions. However, even though various technologies are becoming available, there are several socio-environmental constraints that impinge on the viability of ocean energy conversion projects in isolated communities. By assessing environmental restrictions and socioeconomic attributes where electric power may be produced from the ocean can be useful in prioritizing the locations (especially those isolated) where this alternative is more viable. This paper examines socio-economic and environmental factors that may affect the introduction of ocean energy harvesting in areas currently without electricity. Our findings reveal that: a) in the coastal area of the state of Michoacán, southwest Mexico (at < 20 km from the coast and <100 m.a.s.l.), 153 human settlements with over 4,000 inhabitants lack electric power; 16 of these settlements are indigenous; b) economic activities are mostly fisheries and ecotourism; yet, marginalizaion is very high in the area; c) there are four protected areas with nesting sites for several marine turtle species (greater black, hawksbill, leatherback, and green); the "Deep Pacific Sea" natural protected area harbors great biodiversity; and d) electric power may be produced from ocean energy, especially waves, currents and thermal gradients. The infrastructure for grid connection and technical and logistical support is limited, and the topography near the coast is complex. However, our results indicate that the coastal region of Michoacan, has promising sources of ocean energy, especially for isolated settlements with limited, or no, electricity supply. The results show that waves and thermal gradients are viable options for energy generation in the area studied. Considering socioeconomic conditions and environmental restrictions, our observations suggest that, in particular, ocean energy projects might be successfully implemented in two locations on the coast of Michoacan, Future on-site studies into the environmental impact, the percepction and acceptance of society towards the new technologies and economic costs are necessary before implementing these new technologies.

1. Introduction

Ocean energy resources can be harnessed to provide an alternative to fossil fuels, either on a large scale, in regions with high availability of resources, or at a smaller scale, covering basic power needs for settlements located in coastal regions. In developing countries in particular, it is common to find isolated areas with no electricity at all (Ahuja and Tatsutani, 2009), while nearby, in some cases, it is possible that ocean energy resources are available to produce electric power. However, it may be that making use of these resources would be limited because of environmental and socio-economic constraints (Bonar et al., 2015; Felix et al., 2019).

Recent reviews of global energy resources have shown the immense potential for energy production that exists in the ocean (from currents, tides, waves, temperature and salinity gradients); significantly greater than the demand for electricity (Melikoglu, 2018). Tidal power was estimated to offer almost 1000 TW-hours (TWh); wave power, up to 93,000 TWh; temperature gradients

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87,600 TWh; and salinity gradients between 2000 and 5200 TWh, maybe even up to 27,700 TWh. This explains why several countries around the world are hoping to satisfy their energy demands by generating electrical power from ocean resources. In many cases this has not yet been possible on a large scale as most ocean energy technologies are still being developed. Furthermore, economic, technical and environmental factors often limit the implementation of this technology (Quitoras et al., 2018).

Studies on ocean energy resources in developing countries worldwide have been undertaken for wave, current and thermal gradient potentials. For instance, in Latin-America, López et al. (2015) evaluated the available wave energy resources in Peru using numerical simulations. These authors concluded that the available resources are about seven times the total electricity demand of Peru and that, because of its low temporal variability, harnessing wave energy is possible. Similarly, Kirinus et al. (2018) evaluated the potential of generating electricity from ocean currents off the coasts of Brazil using numerical analyses. With the methology employed, they identified prospective regions for the deployment of devices in areas with high current intensity in the south of Brazil. Woodhouse and Meisen (2011) estimated that the ocean and tidal energy potential of Chile is enormous, especially along the Southern coast, with an estimated potential of 164,000 MW off Central and Southern Chile. In Mexico, García Huante et al. (2018) evaluated the potential of ocean thermal gradient energy conversion with data simulation, concluding that the sites with greatest potential are off the southwestern coasts. Also in Mexico, for potential tidal energy, Mejia-Olivares et al. (2018) proposed sites in the Gulf of Baja California, whereas for ocean currents, Alcérreca-huerta et al. (2019) suggested locations around the island of Cozumel.

The use of clean energy sources is an alternative to using fosil fuels for energy production in developing countries with access to the oceans, as long as it is socially adequate, environmentally safe, technically feasible and economically viable. Mexico is an example of an emerging country with extensive coastlines; off the Atlantic and Pacific Oceans there are many potential sources for the generation of electricity. Mexico currently obtains 27% of its electric power from hydroelectricity, but it is planned to diversify power sources to include geothermal, wind and natural gas (González-Ramírez et al., 2017) and ocean energy is being considered. The goal of the federal government is for 35% of all electricity generation to come from sustainable technologies by 2024 (SENER, 2012).

The first step in implementing ocean energy extraction projects is an evaluation of the resources available, in order to identify prospective sites. This may be done from available ocean parameter databases, obtained from numerical simulations of ocean behavior, as was carried out by Aboobacker et al. (2017), Alonso et al. (2017), Bento et al. (2018), Hossain et al. (2013), Kamranzad et al. (2017), Masutani and Takahashi (2010), and Yang et al. (2013), among others. Next, key aspects should be addressed, including the technologies available, infrastructure, marine and coastal governance, costs, environmental impact and legislation (Borthwick, 2016). Besides these factors, social and economic constraints should be considered before determining potential sites for energy extraction (Dalton et al., 2015; Hernández-Fontes et al., 2019; Zhang et al., 2019). For instance, there are some coastal regions with ethnic communities and cultural traditions, which ought to be preserved. In addition, the perception and acceptance of ocean energy by these communities should also be considered before promoting such development. Thus, sociological studies would be appropriate, to analyse the potential impact (and acceptance) of ocean energy projects.

Environmental information on the potential impacts of ocean energy production should also be gathered (Mendoza et al., 2019). Some locations are particularly diverse in terms of ecosystems or species (Basurko and Mesbahi, 2014; Felix et al., 2019). For instance, a wide variety of ecosystems (mangroves, coastal lagoons, sea-grass beds, coral reefs, coastal dunes) may coexist in protected areas along the coast. In other locations, endemic keystone species may be present (Saeedi et al., 2019). Thus, if we want ocean-based energy production to be environmentally friendly, the potential environmental impact must first be assessed, and an environmental baseline determined.

Once the potential social and economic constraints, environmental restrictions, and the power availability are known, a decision-making process to find suitable locations for the installation of ocean energy devices can be carried out using a Geographic Information System (GIS). This type of analysis is useful when making decisions which involve many technical and non-technical factors, that are spacially explicit (Murrant and Radcliffe, 2018). Such an approach has already been used to define prospective sites for ocean energy projects in developed countries, such as Australia (Flocard et al., 2016) and Portugal (Castro-Santos et al., 2019). However, to the best of the authors' knowledge, social and environmental aspects have not yet been discussed in detail regarding developing regions with isolated communities.

Until now, very few studies have been performed to discuss off-grid renewable energy alternatives for providing electricity in developing regions where there are isolated communities. For instance, Sánchez et al. (2015) suggested some alternatives for isolated communities in the Amazon region, in Brazil, including hydrokinetic energy from rivers, biomass from direct burning or gasification, biofuels and hybrid alternatives such as the combination of solar and wind energies. For iolated communities in the southeast of Brazil, Baschiera and Fagnani (2018) evaluated the possibilities of providing photovoltaic electrification forn isolated river island communities. More recently, Curto et al. (2019) discussed the possibility of combining solar, wind and sea wave energy to provide electricity in the Balearic Islands and Fiji. In this type of assessments, low scale electricity production, which can be stored in batteries, can be very useful for simple but important necessities, such as allowing people to read at night, to pump a small amount of water, or listen to ratio news (Ahuja and Tatsutani, 2009). Although different types of renewable energies and related socio-environmental constraints have been defined as alternatives for grid and off-grid electricity connection in developing countries, the research regarding the emerging ocean energies for this still requires investigation regarding the benefits and constraints involved in possible projects. For instance, Martínez et al. (Unpublished data) found a total of 10,996 references that mentioned at least one of the alternatives for ocean energy production, which highlights the current interest in the topic. Despite this importance, studies on the potential environmental impacts of ocean energy devices are generally lacking, and only 140 deal directly with environmental issues; a very small percentage of the literature (Table 1). In addition, the number of studies that explored socio-economic conditions in locations where ocean energy production is feasible was even more scarce. That is, besides assessing the environmental, economic and social limitations, it is also necessary to estimate, at least in a preliminary way, the amount of ocean energy power that can be harnessed to predefine prospective technologies. To our knowledge, there is no study in which ocean energy production is analysed while potential environmental impacts and socioeconomic conditions are explored simultaneously for isolated locations.

With these factors in mind, this paper explores some of the environmental and socio-economic factors to consider in examining the possibilities of initiating ocean energy extraction at sites in remote regions, off the coast of Michoacan, in southwestern

Table 1
Number of settlements without electricity in Mexico, by state. Coastal localities were defined by being at < 100 masl, and less then 10 km from the coast). Coastal states are highlighted in grey.

STATE	Coastal	Non-coastal	Total	% of coastal
Aguascalientes		8	8	
Baja California	18	42	60	30.0%
Baja California Sur	14	24	38	36.8%
Campeche	2	33	35	5.7%
Chiapas	21	977	998	2.1%
Chihuahua		441	441	
Coahuila de Zaragoza		43	43	
Colima	3	13	16	18.8%
Distrito Federal		7	7	
Durango		513	513	
Guanajuato		94	94	
Guerrero	11	633	644	1.7%
Hidalgo		83	83	
Jalisco	2	407	409	0.5%
Mexico		66	66	
Michoacan de Ocampo	21	316	337	6.2%
Morelos		28	28	
Nayarit	2	239	241	0.8%
Nuevo Leon		77	77	
Oaxaca	11	392	403	2.7%
Puebla		45	45	
Queretaro		67	67	
Quintana Roo	8	10	18	44.4%
San Luis Potosi		263	263	
Sinaloa	2	199	201	1.0%
Sonora	10	89	99	10.1%
Tabasco		51	51	
Tamaulipas	17	209	226	7.5%
Tlaxcala		10	10	
Veracruz de Ignacio de la Llave	51	547	598	8.5%
Yucatan	1	50	51	2.0%
Zacatecas		49	49	

Mexico, an area with many isolated communities in sore need of electric power. Based on the above, our goal was to identify prospective localities where it is viable and sustainable to develop ocean energy production that would benefit those locations with the hardest socioeconomic conditions and that is environmentally friendly. To do this, topographic conditions, areas restricted for diversity conservation, the distribution of potential isolated communities, main economic activities, and infrastructure availability, were considered for the coast of Michocan, in the first part of this work. Then, a theoretical assessment of ocean energy from currents, waves and thermal gradients close to the coast of Michoacan was carried out using engineering approaches (Hernández-Fontes et al., 2019). With a knowledge of the constraints and the ocean energy possibilities, a qualitative analysis was carried out to suggest locations where it would be most beneficial for isolated coastal regions, considering the social needs, while remaining environmentally sustainable.

The study is divided as follows: First, we describe the methods employed for the analyses, including relevant information on the state of Michoacan, socio-environmental conditions and restrictions and the methods employed for the theoretical estimation of ocean energy power. Next, in the results, we describe the socioeconomic attributes of those coastal locations in Michoacan that are still in need of electric power, as well as the environmental elements that could be affected by ocean energy production. We then analyse the potential and availability of ocean energy production. With the information gathered we performed a qualitative analysis to discuss the possibilities of ocean energy harnessing in Michoacan. Estimating the costs of these projects was not within our goals and would merit a new whole study by itself. However, we are highly aware of the relevance of such analysis before implementing an ocean energy project.

2. Methods

Based on our goals, this study was divided into three sections. First, we identified the settlements that are closest to the coast in Michoacan and which have limited, or no, electricity. Then, we analysed the socioeconomic and environmental features of these settlements and identified those where an electricity supply from the ocean is feasible, based on the distance from the settlement to the coast. Finally, based on the socioeconomic and environmental constraints that were found, we estimated the potential for producing electricity from ocean energy off the coast of Michoacan. We were thus able to find areas where electricity could be supplied from the ocean, meet the power needs of the local population, and where it is socioeconomically viable and environmentally appropriate. This was done through a combination of different approaches: numerical modelling to determine the power potential; the analyses of public socioeconomic and environmental data, and a qualitative integration of the information, through a geographic information system. We did not analyse the potential economic costs of this project because it would be a thorough study by itself; beyond the scope of this study.

In the following section (Section 2.1), the area studied is presented. Then, we explain how socioenvironmental information was gathered to better describe and understand the societal needs and environmental restrictions for ocean energy production in these areas (Section 2.2). After this, the methods for defining the ocean energy available from currents, waves and thermal gradients are explained (Section 2.3). Finally, the GIS technique with which all the information is integrated, analysed and described (Sect. 2.4).

2.1. Case study

2.1.1. Overview of energy production and needs in Mexico

Mexico is a developing country with its own environmental, economic and social factors that need to be considered when planning ocean energy development. Factors restricting this include the ecologically important Natural Protected Areas on and off the coasts, the existence of indigenous communities with their unique traditions, the presence of coastal communities without access to electricity, fishing activities and other economic activities dependent on the ocean, and limited infraestructure along the coast.

With a population of over 120 million, Mexico has 1.3% of homes with no electricity (INEGI, 2015). The national electricity company, Federal Comission of Electricity (CFE), (SENER, 2015), reported the deficit in electrification across the republic (Table 1). Seven of the ten states where electrification is most needed are coastal (Chiapas, Guerrero, Veracruz, Jalisco, Oaxaca, Michoacan and Nayarit). Furthermore, in the coastal states of Quintana Roo, Baja California and Baja California Sur, a large percentage of locations lacking electricity are found on the coast (Table 1), ranging from 30% (Baja California) to 44% (Quintana Roo).

The 17 coastal states have a significant number of homes without a supply of electric power (Table 2, Fig. 1). According to the Intercensal Survey (INEGI, 2015), between 0.6 and 2.48% of homes in coastal states lack electricity (Table 2). In most cases, the homes that do not have electricity are found in places that are difficult to reach, due to the terrain. In addition to the numbers given, there are also likely to be isolated homes that were not considered in the census. Isolated communities are most common in the southwestern coastal states such as Chiapas, Guerrero, Oaxaca and Michoacan. These states have a complex topography, heterogeneous environmental conditions, high biodiversity, and many

Table 2
Availability of electricity in homes in the Mexican coastal states, 2015, according to the Intercensal Survey described. The percentages show homes with electric power (Y), without it (N), and the homes for which there was no information (NI). (INEGI, 2015).

State	Total of private inhabited homes	Y (%)	N (%)	NI (%)
Baja California	961 533	99.29	0.68	0.03
Baja California Sur	208 972	98.44	1.39	0.18
Campeche	244 299	98.08	1.88	0.04
Colima	204 949	99.38	0.56	0.05
Chiapas	1 238 565	97.54	2.33	0.13
Guerrero	894 621	97.34	2.48	0.18
Jalisco	2 058 775	99.55	0.37	0.08
Michoacan	1 191 405	98.97	0.97	0.12
Nayarit	332 279	97.87	2.07	0.06
Oaxaca	1 042 941	95.03	3.11	1.86
Quintana Roo	440 663	98.76	1.19	0.05
Sinaloa	805 854	99.27	0.64	0.08
Sonora	812 567	98.01	1.34	0.65
Tabasco	656 059	99.32	0.57	0.11
Tamaulipas	986 886	98.79	0.95	0.26
Veracruz	2 250 001	98.08	1.84	0.08
Yucatán	564 613	98.62	1.31	0.08

innaccesible settlements located relatively close to the coast. The highest concentration of ethnic groups in Mexico are also found here. As it is considered necessary to provide electric power to such isolated communities, at least on a small scale, ocean energy may a viable alternative. Such is the case for the southwestern region of Mexico, where different ocean energy sources (wave, ocean currents and thermal gradients) are potentially available off the coasts (García Huante et al., 2018; Hernández-Fontes et al., 2019). In this study we focused on the coastal area of the state of Michoacan.

2.1.2. The state of Michoacan

Michoacan is located between 100° 04’ - 103° 44′ W and 20° 24’ - 17° 55′ N, (Fig. 2). Even close to the coastline, the state is mountainous, with a maximum altitude of 3,840 m. The main geographical feature of the coast are the pocket beaches between extensive areas of cliffs. Michoacan has 228 km of coastline, from the river Coahuayana, at the border with the state of Colima, to the mouth of the river Balsas, bordering the state of Guerrero, along which there are only 24 beaches with road access.

In Michoacan, three types of energy are currently used to produce electricity: biomass (0.5%), geothermal (39.73%) and hydraulic (59.72%). Table 3 shows the location of the power stations in the state, as well as its type, the power station capacity (PSC) in MW, and the generation of energy (GE) in (GWh/year) (INEL, 2016). Hydraulic energy is the main source of electricity (1765 MW), followed by geothermal energy. Up to now, the capacity of biomass energy production is still very small. As in the rest of the country, most energy production comes from the state-run electricity generating company, CFE.

From Table 3 it can be seen that Michoacan depends almost entirely on water for its electricity production, via lakes, rivers, aquifers, etc., though hydroelectric power stations and thermoelectric generation, that uses large volumene of water for the cooling systems. In Michoacan, as in other Mexican states, surface water is an increasingly valuable resource that will become scarcer, due to over-exploitation. Therefore, it is wise to find alternative sources for electric power generation, such as ocean resources.

2.2. Socio-environmental conditions and restrictions

Three databases were used to describe and analyse the socio-environmental conditions and restrictions in locations without electricity. Socio-economic variables were collected from INEGI databases, whereas environmental conditions were based on the

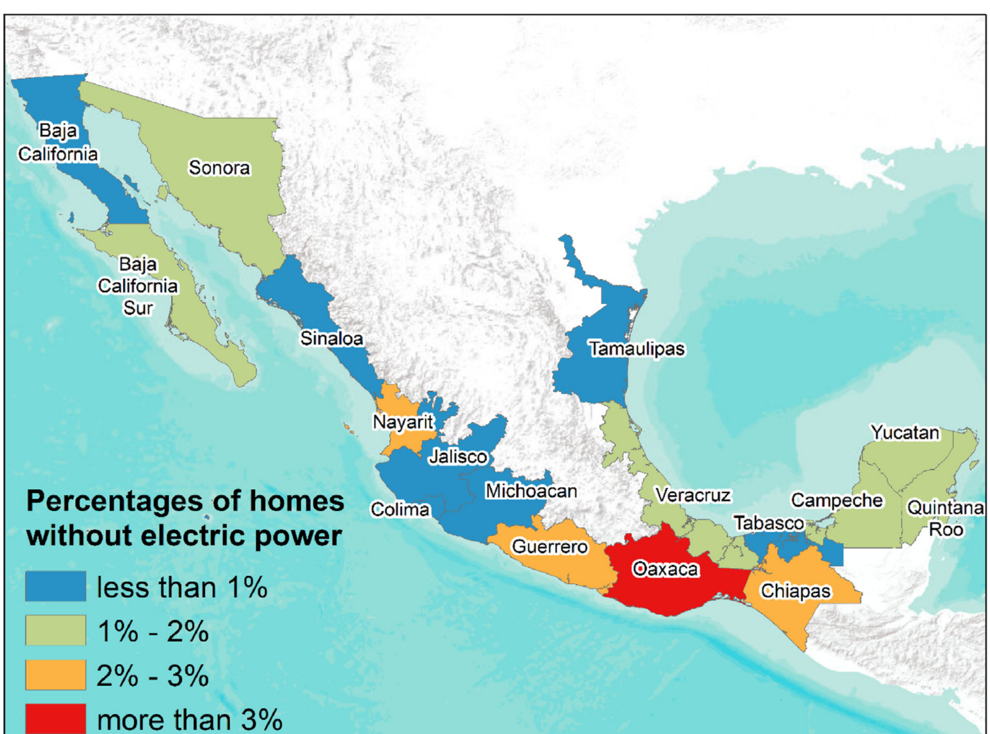

Fig. 1. Unavailability of electricity in homes in the Mexican coastal states, 2015, according to the Intercensal Survey described (INEGI, 2015).

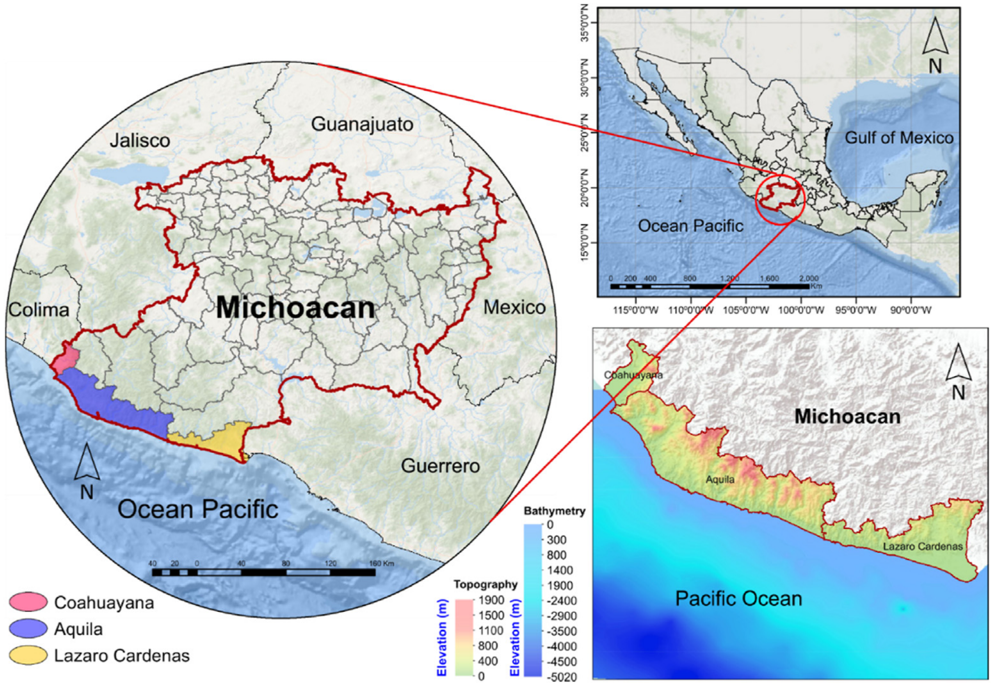

Fig. 2. Geographic localization of the state of Michoacan, showing its three coastal municipalities.

Table 3
Generating plants producing electric power in Michoacan (INEL, 2016).

Energy type	Municipality	Power station name	Sector	Type	PSC (MW)	GE (GWh/year)
Biomass	Taretan	Ingenio Lazaro Cardenas	Private	Direct combustion	5.50	9.98
Biomass	Tocumbo	Ingenio Santa Clara	Private	Direct combustion	9.10	12.77
Geothermal	Cd. Hidalgo	Los Azufres	Government	Geotermal plant	225.00	1,647.78
Hydraulic	Tacambaro	Bartolinas	Government	Small hydroelectric	0.75	0.79
Hydraulic	Panindicuaro	Botello	Government	Small hydroelectric	18.00	27.08
Hydraulic	Uruapan	Cupatitzio	Government	Large hydroelectric	80.00	231.71
Hydraulic	Zamora	El Cobano	Government	Large hydroelectric	60.00	124.94
Hydraulic	Arteaga	Central El Infiernillo	Government	Large hydroelectric	1,200.00	1,249.75
Hydraulic	Periban	Itzicuaro	Government	Small hydroelectric	0.62	0.97
Hydraulic	Lazaro Cardenas	La Villita	Government	Large hydroelectric	320.00	572.36
Hydraulic	Jacona	Platanal	Government	Small hydroelectric	12.60	17.88
Hydraulic	Villa Madero	San Pedro Poruas	Government	Small hydroelectric	2.56	1.32
Hydraulic	Morelia	Tirio	Government	Small hydroelectric	1.10	1.18
Hydraulic	Uruapan	Zumpimito	Government	Small hydroelectric	8.40	22.46
Hydraulic	Uruapan	GOB de Michoacan	Private	Small hydroelectric	4.05	14.98
Hydraulic	Contepec	Generadora Fenix, S. A. P. I. de C. V., Central Lerma	Private	Large hydroelectric	35.00	173.19
Hydraulic	Contepec	Generadora Fenix, S. A. P. I. de C. V., Central Lerma 3	Private	Small hydroelectric	22.00	38.47

Table 4
Engineering approaches to estimate the theoretical power from waves, currents and thermal gradients (Hernández-Fontes et al., 2019).

Waves (Salter, 1974)	Currents (Kabir et al., 2015; Meyer and Van Niekerk, 2016)	Thermal gradient (Nihous, 2007; Rajagopalan and Nihous, 2013a)
$P_w = \frac{\rho g^2}{64\pi} H_s^2\, T$	$P_c = \frac{1}{2}\rho \overline{V}^3$	$P_{GT} = \frac{3\rho c_p Q_{ww} \gamma \Delta T^2}{16\, T_{fs}(1+\gamma)}$

presence of protected areas because of their biodiversity and the presence of endemic species (CONABIO). Such information was integrated into the geographic information system (GIS), for the area less than 10 km from the coast and less than 100 masl.

2.3. Theoretical ocean energy potential

The theoretical power available from waves, currents and thermal gradients in Mexico was estimated with the engineering approaches summarized in Table 4 (Hernández-Fontes et al., 2019).

For the wave power (P_w, in W/m), ρ is water density (in kg/m^3), g is the acceleration due to gravity (in m/s^2), H_s is the significant wave height (in m), and T is the significant wave period (in s). For the power due to currents (P_c, in W/m^2), V is the resultant ocean current velocity (in m/s) assumed at 0 m depth. For the power due to thermal gradient energy (P_t, in W), c_p is the specific heat of water

(~4 kJ/kg°K), Q_{ww} is the discharge of the warm water, considered as $Q_{ww} = \gamma Q_{cw}$, where $Q_{cw} = 250$ kg/m^3 is the cold water discharge, considering an OTEC plant of 100 MW (OSBoard, 2013). T_{fs} is the water temperature at the free surface and ΔT is the thermal gradient (T_{500}-T_{fs}), where T_{500} is the water temperature at 500 m depth.

2.3.1. Databases

Two databases were used to determine the parameters employed in the formulae summarized in Table 4. The variables H_s and T were considered from the Era-Interim database (ECMWF), further details are found in (Dee et al., 2011). Ten-year data (reported daily at 12:00 h) from September 1, 2008 to August 31, 2018, at a spatial resolution of 1/6° was used.

The horizontal and vertical components of the water velocity V at 0 m depth and the water temperatures T_{fs} and T_{500}, were all obtained from the HYCOM reanalysis database (details in Bleck, 2002). Ten-year data, from September 1, 2008 to August 31, 2018, was used as before, but with a spatial resolution of 1/12°. It is important to mention that this period of time was chosen according to the available simulation data.

Unlike the Era-Interim database, the HYCOM data lacks a temporal resolution to consider several years in the analyses but it has an excellent spatial resolution to consider regions closer to the coasts.

The specific validation of the databases used to estimate the energy potentials in the south-Pacific coasts of Mexico has been difficult to achieve, due to the lack of measuring devices in this region (Ribal and Young, 2019). However, the reliability of the data employed has been assumed from their validation in regions where data from measuring devices are available. For instance, the reliability of ERA-Interim data has been demonstrated through validations performed with data from available altimeters and buoys in the Atlantic coasts of north-America (Muis et al., 2019), the west coast of the United States (Aarnes et al., 2015) and regions in the Pacific Ocean (Hemer et al., 2011). With respect to the water temperature and velocity HYCOM data, their reliability has been demonstrated through validation in works such as (Metzger et al., 2010). For the theoretical power estimation of this work, the simulation databases used are considered acceptable for a preliminary theoretical estimation. Further technical and practical assessment of resources will require simulations with at a higher spatio-temporal resolution, and validation with measurements at more specific locations.

2.4. GIS methods

We used the CEM 3.0 model (Continuous Mexican Elevations) from INEGI to map the topography of the state of Michoacan. Then, elevations of less than 100 m were selected, shown by shading from the CEM 3.0 (Hillshade calculated in QGIS 3.6.1-Noosa).

Afterwards, using the database of CFE (advances in electrification) each of the localities was geographically located, assigning latitudes and longitudes. The geographical coordinates were obtained from the 2010 INEGI population and housing census. For each locality a unique code with 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. The settlemants considered for the present study are those requiring electrification and at an altitude of less than 100 masl and at a diststance from the coast of less than 10 km.

3. Results

3.1. Socio-economic and environmental aspects

3.1.1. Coastal settlements with and without electricity

Overall, the number of settlements and inhabitants lacking electricity is relatively small, but nonetheless it is very important (Table 5). There are 20 coastal settlements at less than 100 masl, with 518 inhabitants. 48 localities are less than 10 km from the coast, with 1,318 inhabitants.

Due to the complex topography of Michoacan, with the Sierra Madre del Sur mountain range very close to the coast, at altitudes over 100 masl and more than 10 km from the coast, both the number of settlements and of inhabitants without electric power in their homes is almost five times higher than the figures given in Table 5.

There are three, widely contrasting, municipalities on the coast of Michoacan: Lazaro Cardenas, Aquila and Coahuyana (Fig. 2). The numbers of localities and inhabitants that could potentially benefit from ocean energy production vary for the three municipalities (Fig. 3). Lazaro Cardenas, with an extension of 1,160 km^2, has a population of 178,800, who live in approximately 50,000 homes of which 1% do not have access to electricity. Aquila has an extension of 2,300 km^2, with only 23,540 inhabitants living in 4,950 homes, of these 44% do not have electricity. Coahuayana is much smaller, 362 km^2 and has a population of 14,140 inhabitants, living in 3,630 homes, of which 2% do not have electricity (INEGI, 2010).

- In Lazaro Cardenas, there are only 8 settlements at less than 10 km from the coast. Of these, five are at less than 100 masl. The total number of people that could potentially benefit from ocean energy production adds a total of 117.
- In Aquila, in turn, a total of 40 settlements are within 10 km from the shoreline, and of these, 15 are at an altitude lower than 100 masl, giving a total of 100 people that would benefit from ocean energy.
- Finally, Coahuayana there are no homes lacking electricity within10 km of the coast and at less than 100 masl, so ocean energy production here would involve transferring the power to very inaccessible locations.

In addition to those communities without (or with a limited) electricity supply, other coastal settlements could also benefit from ocean energy to strengthen already existing electric power supplies and devices. Thus, we also considered some other settlements, less than 100 masl and within 10 km of the coast. Fig. 4 shows the main settlements located near the coast of Michoacan. Their main characteristics are listed in Table 6. Thus, besides those localities with incomplete electric power supply, an additional 52 were considered, adding a total of 151,973 inhabitants that could also benefit from ocean energy production.

In this area, the marginalization of communities is associated with lack of opportunities and insufficiencies of goods and services fundamental to human well-being. The social vulnerability of marginalized communities is severe, creating increasingly unfavorable conditions because of unequal access to well-being. To assess the level of marginalization, the National Population Council (CONAPO), analizes nine forms of exclusion, with an indicator for each variable. The criteria considered include education level, living conditions, income and, interestingly, the number of inhabited private dwellings without electricity (CONAPO, 2010). The index produced, using official data from INEGI, describes the marginalization of communities as: very high, high, medium, low and very low. The first and the last categories would be assigned to the communities with greatest and least socioeconomic vulnerability,

Table 5
Coastal settlements without electricity in Michoacan at different altitudes and distances from the coast. Data from INEGI (2010).

Altitude/distance from the coast	Number of settlements	% of settlements lacking electricity	Inhabitants	% of inhabitants lacking electricity
<10 msnm	6	3.92	151	3.64
<100 msnm	20	13.07	518	12.48
<10 km from the shoreline	48	31.37	1,318	31.74
<20 km from the shoreline	135	88.24	3,732	89.88
Total (<20 km and <100 msnm)	153		4,152	

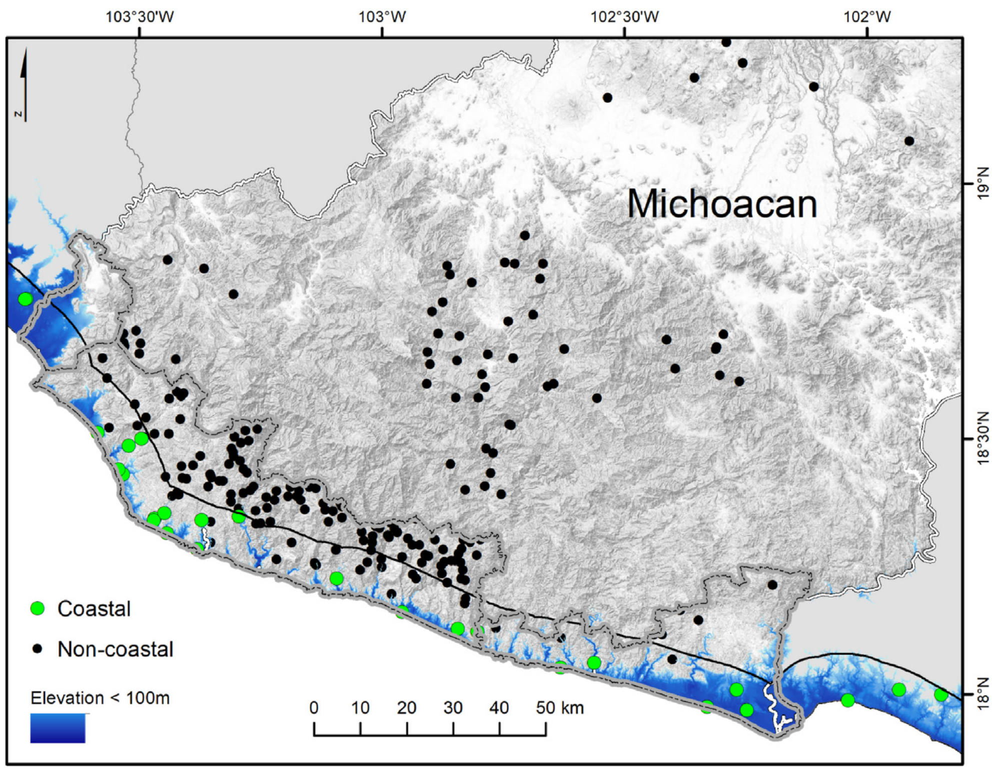

Fig. 3. Settlements without electricity in Michoacan. Settlements were considered "coastal" when they were at an altitude lower than 100 masl, and at less than 10 km from the coast.

respectively.

Aiming to plan an efficient development of ocean energy supply, these coastal settlements were prioritized based on three criteria: (i) those with more than 100 inhabitants; (ii) those within 10 km of a main road, along which electricity could be distributed; and iii) those with a high or very high level of marginalization. The last criterion is particularly relevant because having access to electricity in these locations could significantly improve human well-being. Fig. 5, shows the settlements where these three criteria are met.

It is evident that the level of marginalzation of coastal localities in Michoacan is very high, which means that they would experience a substantial social benefit if electricity was brought to them. It is important to mention that beyond our "coastal" definition, many marginalized settlements are found. Other energy sources should be considered to comprensively face the lack of electricity here.

In addition to the priorization based on socioeconomic conditions, before the installation of new devices, it is important to consider social perception and acceptability of new energy production, which could be a challenge to be addressed. In the three coastal municipalities that were studied, we found 16 settlements with a total of 279 indigenous inhabitants (Fig. 5), that were filtered according to the two previously described criteria (INPI, 2018).

3.1.2. Economic activities

The port of Lazaro Cardenas is one of the most important links for commerce between Asia and North America (SCT, 2012) requiring considerable amounts of energy. For example the steel complex and associated industries are economically and sociologically very important and have advantageous electricity tarifs.

Further along the coast, Faro de Muserías, La Ticla and Maruata have recently been developed and facilities for ecotourism have begun to be established (Table 6). Here, electricity costs are higher than in other areas and are based on electricity supplied by small solar plants. There is no street lighting in the communities and there is no electricity after 11pm. It is therefore necessary to find alternative electricity sources so that these areas can continue to develop and to fulfill the ecological vision of tourism held for the area. Improving the electricity supply for the tourist facilities will bring down energy costs for the population in general and provide a boost to the tourist industry.

There are some smaller, but important, economic activities that could be impacted by the environmental changes associated with the implementation of ocean energy projects off the Michoacan coast. The fishing and eco-tourism activities, common on the beaches of Aquila, are examples. However, while the effects of an energy conversion project on fishing areas is beyond the scope of this

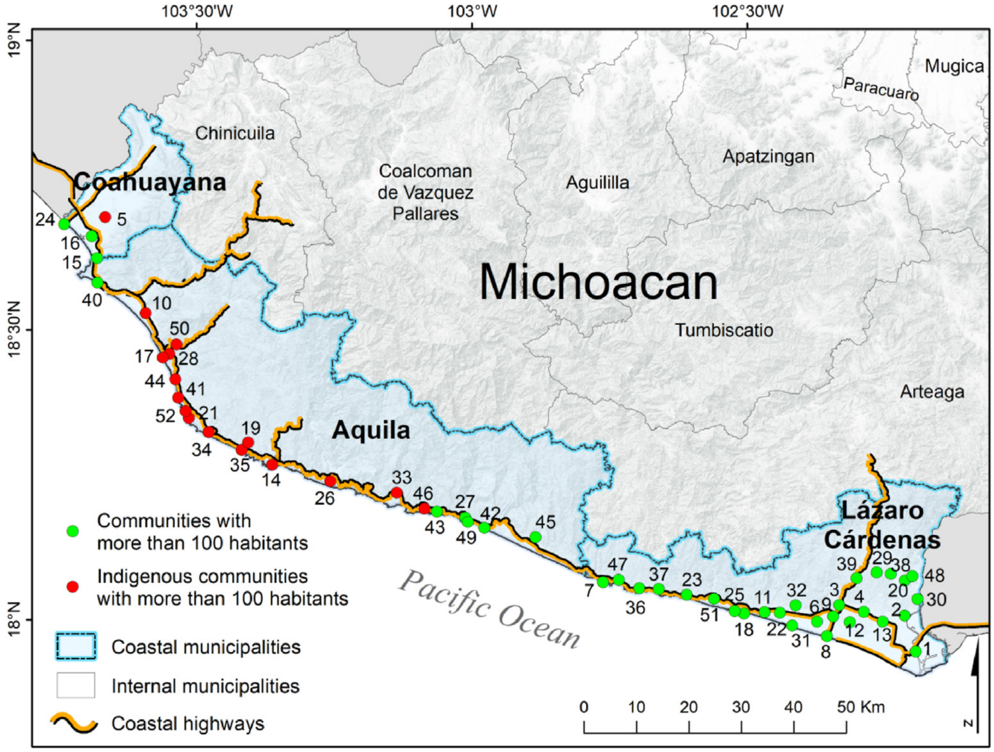

Fig. 4. Settlements and communication routes on the coast of Michoacan.

work, this was the main focus of the study, as along the entire coastline, this is the main economic activity. One of the main objectives of any ocean energy project would be to avoid any conflicts with local economic, social or cultural activities. Therefore, we mapped fishing settements (Fig. 6, Table 7), obtained from the Atlas of Fishing Locations of Mexico (Ramírez-Rodríguez et al., 2006). When considering the deployment of ocean energy devices, a radius of about 4 km around the potential locations should be examined, since Mexican fishing zones are usually found on the continental shelf, where there is an average depth of 200 m (Cifuentes Lemus, 1979). In Michoacan this is about 4 km offshore.

3.1.3. Environmental restrictions

In Mexico, Protected Natural Areas must be designated through a Presidential Decree and are subject to special regimes of protection, conservation, restoration and development (CONAMP, 2016). These are areas where the original environment has not been significantly altered by human activities, and where it is believed that the natural ecosystems should be preserved or restored. Off the Michoacan coast, in the Exclusive Economic Zone (Fig. 7), as of November 2017, there are three protected areas. The beaches of Maruata and Colola, is a nesting zone for the Greater Black turtle. The rocky outcrops of this area are also suitable for juvenile Hawksbill turtles (ICAPO, 2014). The second Natural Protected Area is the beach at Mexiquillo, which is considered one of the five most important beaches in the Mexican and Mesoamerican Pacific for the Leatherback turtle. The Olive Ridley sea turtle and the Green turtle also nest here (RAMSAR, 2004). Finally, around El Caimán lagoon, the mangroves have biological importance and should be preserved.

In addition to the areas described above, the Deep Mexican Pacific (Fig. 7), is also considered a Natural Protected Area because of its unique ecosystems and habitats where highly adapted and specialized species and populations live, such as benthic invertebrates, benthic and demersal fish. These sites are all strategic places for biodiversity and are characterized by warm temperatures throughout the year, essential for the development of tropical marine fauna (DOF, 2016).

The flora and fauna of these areas should be protected and therefore this imposes important constraints on ocean energy projects. Having avoided the protected areas off the coast in our case study, only a small area of ocean remained, as highlighted in (Fig. 7).

3.1.4. Distance to infraestructure

Existing infrastructure is vital in any project to deploy and operate ocean energy conversion devices (Flocard et al., 2016). So too the requirements of grid connection, transport routes, inspection and control activities, supplies and transport of materials for construction, operation and mainatenance.

Fig. 8 shows the main road that runs along the entire coastline of Michoacan, linking the most important ports and the main electricity substations. The main ports on this section of the Pacific are Lazaro Cardenas, in Michoacan, and Manzanillo, further north in the state of Colima. The first is a leading industrial and commercial port (SCT, 2012), while Manzanillo is the main entrance for international trade in the central area of Mexico (API_Manzanillo, 2019). With respect to the electrical substations, which may be important for connection to the national grid, Coahuayana substation is almost on the border with Colima and the San Isidro substation is close to the limits with Guerrero.The most suitable places for grid connection would be close to the main substations. On the other hand, selecting connection points close to the main road could also be an alternative for selecting potential sites to install small substations. The ports of Manzanillo and Lázaro Cardenas would provide easy access to supplies for the devices and substations. However, it remains clear that access to the remote locations is difficult.

Table 6
Description of the settlements located along the coast of Michoacan (INEGI, 2015; INPI, 2018). Δ shows settlements with indigenous inhabitants.

	Settlements	Population (habitants)	Longitude (°)	Latitude (°)	Elevation (m)	
1	Lázaro Cárdenas	63732	102.13	18.00	20	
2	Guacamayas	36724	102.12	18.01	20	
3	La Mira	14224	102.19	18.02	40	
4	Buenos Aires	9551	102.17	18.01	60	
5	Coahuayana de Hidalgo	6037	103.40	18.42	10	Δ
6	Playa Azul	3193	102.21	17.59	10	
7	Bahía Bufadero	2065	102.45	18.04	30	
8	El Habillal	1821	102.22	18.00	20	
9	Acalpican De Morelos	1727	102.20	18.01	20	
10	La Placita De Morelos	1274	103.35	18.32	20	Δ
11	Chucutitán	770	102.28	18.01	10	
12	El Bordonal	689	102.18	18.00	40	
13	Puente de La Vía	613	102.15	18.00	40	
14	Maruata	491	103.21	18.16	10	Δ
15	Ojo de Agua de San Telmo	474	103.40	18.37	20	
16	El Ticuiz	469	103.41	18.39	10	
17	La Ticla	420	103.33	18.27	10	Δ
18	Las Pecas	395	102.30	18.01	20	
19	Colola	395	103.24	18.17	10	Δ
20	San Rafael	356	102.12	18.04	100	
21	Faro de Bucerías	347	103.30	18.21	10	Δ
22	Solera de Agua	324	102.26	18.01	20	
23	Chuquiapan	316	102.36	18.03	20	
24	Boca De Apiza	308	103.44	18.41	3	
25	Llanos Del Bejuco	307	102.31	18.01	20	
26	Cachán De Echeverría	286	103.15	18.14	10	Δ
27	Huahua	281	103.00	18.11	10	
28	El Duin	272	103.32	18.27	20	Δ
29	El Reino	270	102.14	18.05	120	
30	La Villita	266	102.11	18.03	20	
31	Las Calabazas	257	102.25	17.60	10	
32	El Colomo	236	102.24	18.02	40	
33	Tizupan	225	103.07	18.13	50	Δ
34	Motín del Oro	206	103.28	18.19	10	Δ
35	Las Haciendas	195	103.24	18.18	20	Δ
36	La Manzanilla	194	102.41	18.03	20	
37	Mexcalhuacan	183	102.39	18.03	20	
38	Las Higueras	182	102.15	18.05	200	
39	San Juan Bosco	181	102.18	18.05	160	
40	Los San Juan de Alima	174	103.40	18.35	5	
41	El Zapote de Madero	168	103.31	18.23	20	Δ
42	Boca de la Manzanilla	165	102.58	18.10	20	
43	Cuilala de Hidalgo	156	103.04	18.12	20	Δ
44	Ixtapilla	149	103.32	18.25	10	Δ
45	El Atrancón	132	102.52	18.09	40	
46	Arenas Blancas	120	103.03	18.11	10	
47	Teolán	118	102.43	18.04	20	
48	La Paz	115	102.12	18.05	80	
49	Campo de Huahua	110	103.00	18.10	10	
50	Cobanera de Ostula	108	103.31	18.28	20	Δ
51	Chuta	102	102.33	18.02	20	
52	La Palma Sola	100	103.30	18.22	20	Δ

Δ = Indigenous populations.

3.2. *Theoretical assessment of ocean energy in Michoacan*

To perform the theoretical assessment of ocean energy from waves, currents and thermal gradients, the study area was taken as the coast of Michoacan, delimited in the Pacific by the limit of the Mexican Exclusive Economic Zone, which extends ~370.4 km (~200 nautical miles) from the coastline. The theoretical power is shown in Fig. 9, Fig. 10 and Fig. 11, in which the average power for 2008–2018, from waves, from currents and from thermal gradients, respectively, was represented by contours.

In Fig. 9 it is seen that the greatest wave power can be found farthest from the coast, with values of 13–14 kW/m. Closer to the coast, values between 11 and 13 kW/m are found. These findings are in good agreement with the worldwide evaluations of wave energy potential performed by Cornett (2008) and Mø;rk et al. (2010), who showed that in Mexico, the Pacific coasts are the regions where the highest wave energy potential can be found.

The theoretical power from ocean currents, Fig. 10, is very low near the coast, 0–4 W/m^2. The most common value for theoretical power is between 16 and 20 W/m^2 further off the coast, while the maximum values are far from the coast, where the power ranges from 24 to 32 W/m^2, agreeing quite well with the results of Hernández-Fontes et al. (2019).

Fig. 11 shows the mean average power from thermal gradients, for depths of over 500 m. Potential power decreases from ~295 to 300 MW in the northwest to ~335–340 MW towards Guerrero. Closer to the coast, values of 315–325 MW are found. The variation between maximum and minumum values is not very significant; ~35 MW. These results are in good agreement with previous evaluations of thermal gradient energy in the Pacific coast of Mexico

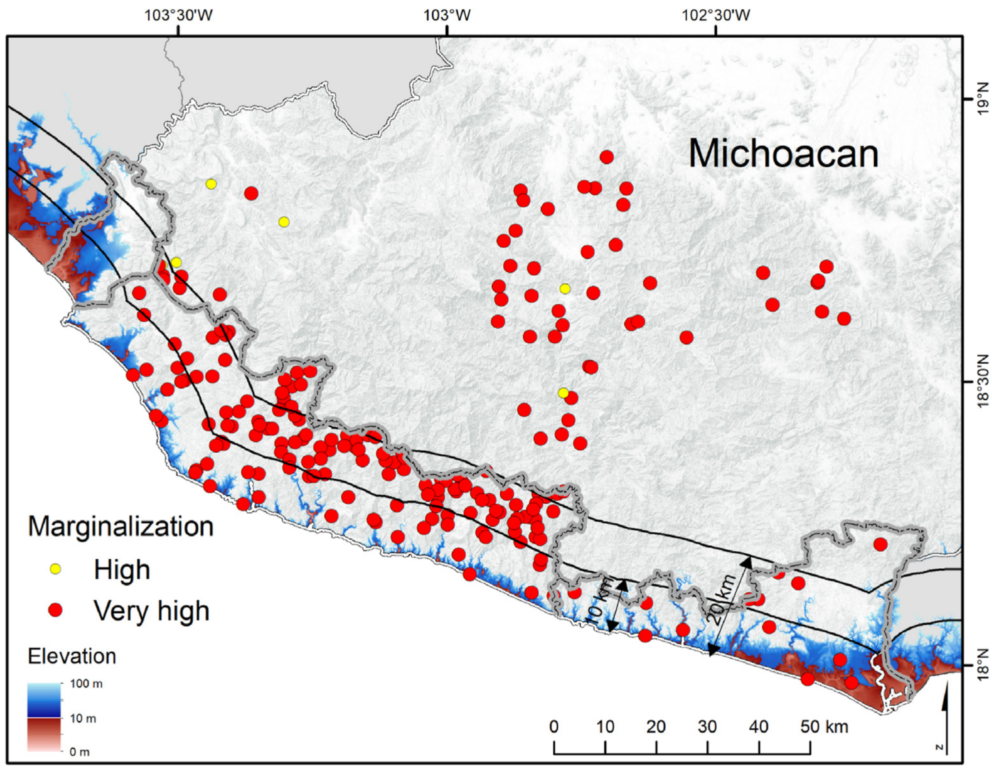

Fig. 5. Marginalized settlements on the coast of Michoacan.

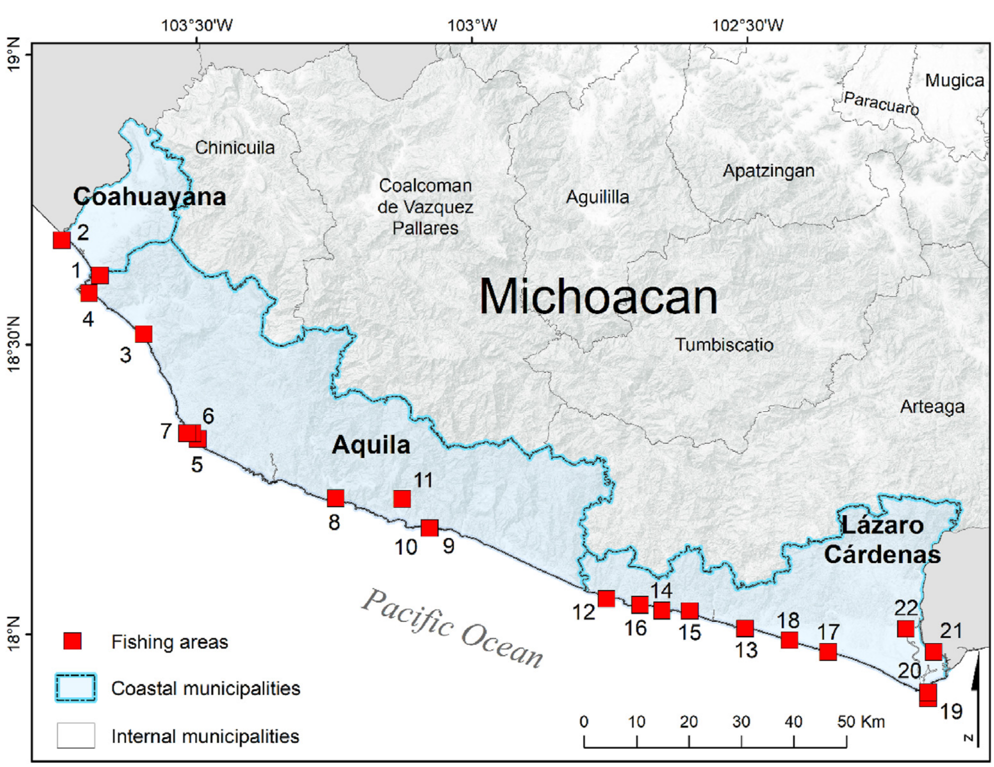

Fig. 6. Fishing settlements on the coast of the state of Michoacan, Mexico.

employing different databases carried out by (García Huante et al., 2018). In fact, this tropical region has a high availability of thermal gradient energy, as seen in the worldwide evaluation of (Rajagopalan and Nihous, 2013b), using an ocean general

Table 7
Name and location of the fishing settlements on the coast of Michoacan (Ramírez-Rodríguez et al., 2006).

	Zone	Longitude	Latitude
1	Punta San Telmo	−103.67	18.62
2	Boca de Apiza	−103.74	18.68
3	La Placita	−103.59	18.52
4	La Privada	−103.69	18.59
5	La Llorona	−103.49	18.34
6	Faro de Bucerías	−103.50	18.35
7	La Manzanilla II	−103.51	18.35
8	Cachán de Echeverría	−103.24	18.24
9	Punta de Pichilinguillo	−103.07	18.19
10	Pichilinguillo	−103.07	18.19
11	Punta Maruata (Piedras Blancas)	−103.12	18.24
12	Caleta De Campos (Bahía Bufadero)	−102.75	18.07
13	Las Peñas	−102.50	18.02
14	Caletilla de Mexcalhuacan	−102.65	18.05
15	Chuquiapan	−102.60	18.05
16	La Manzanilla I	−102.69	18.06
17	Playa Azul	−102.35	17.98
18	Las Calabazas	−102.42	18.00
19	Las 17 Brasas	−102.17	17.90
20	Las 14 Brasas	−102.17	17.91
21	Lázaro Cárdenas	−102.16	17.98
22	Guacamayas	−102.21	18.02

circulation model.

3.2.1. Power availability

The power availability of waves, ocean currents and thermal gradients, was analysed considering the minimum power thresholds as reported by other authors as that required to activate energy conversion devices and in the final study region defined by the environmental restrictions (Fig. 7). The power availability was taken from the percentage of days over the 10-year period where the corresponding threshold was surpassed.

For wave energy, it was decided that to start the operation of a wave energy device (2 kW/m), the minimum characteristic wave height (H_s) is 0.5 m and the related wave period (T) is 4 s x, coinciding with the results of Bernardino et al. (2017). With this power, it would be possible to use wave energy converters that require low amounts of mean wave power to start working. Among these devices are fixed or floating wave activated bodies, point absorbers, oscillating water columns and overtopping devices, whose mean wave power for operation (in kW/m) ranges between 10 and 70, 2.8–80, 4–60 and 14–60, respectively (Mustapa et al., 2017). In the present study, the threshold of 2 kW/m was surpassed 100% of the modeling time, during the 10-year period considered in the entire study area, as shown in Fig. 12a.

For ocean currents, the cut-in velocity, i.e., the velocity to start the motion of hydrokinetic devices, was considered as ~0.4 m/s. With this velocity, it would be possible to use low-production hydrokinetic devices such as the VIVACE (Vortex Induced Vibrations for Aquatic Clean Energy), which take advantage of the vibration produced by vortices (Laws and Epps, 2016). So, with this cut-in velocity, the minimum threshold for current power would be 32 W/m^2. The present evaluation shows that the power availability over the 10-year period in this region does not reach this threshold, as shown in Fig. 12b.

Finally, the required threshold for the performance of the OTEC plant assumed in this work is 100 MW, based on the characteristics of the plant assumed for the power estimation (see Sect. 2.3). This threshold is surpassed 100% of the time, as shown in Fig. 12c. For this case, it is important to mention that the theoretical power is a rough estimate; the effective power will depend on some reduction factors that include losses due to friction and the capacity of the pipes and pumps (Nihous, 2005).

4. Discussion: Potential sites for ocean energy harnessing in Michoacan

In this study we combined socio-economic needs with environmental restrictions and ocean power possibilities, and with these we recommended areas where the installation of ocean energy devices along the southwestern coast of Mexico, in the state of Michoacan is most viable (Fig. 13). Here, the population likely to benefit includes localities with high marginalizarion indices, and

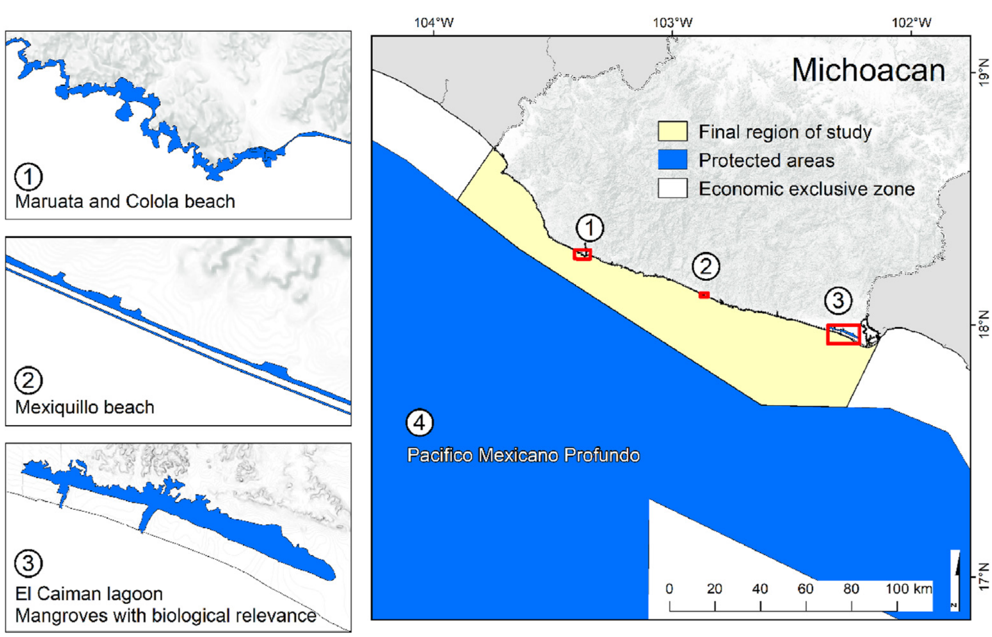

Fig. 7. Natural protected areas in Michoacán (from CONANP- National Commission of Natural Protected Areas). The final study region excludes the coastal restricted areas and the areas of and beyond the Pacifico Mexicano Profundo to the Economic exclusive zone.

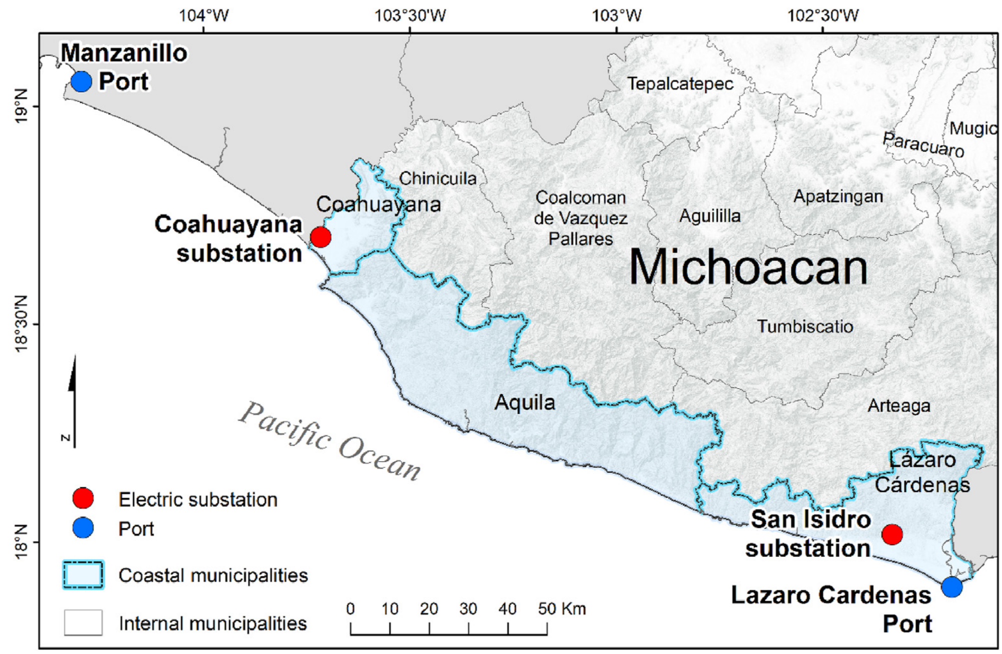

Fig. 8. Ports and electricity substations near to Aquila.

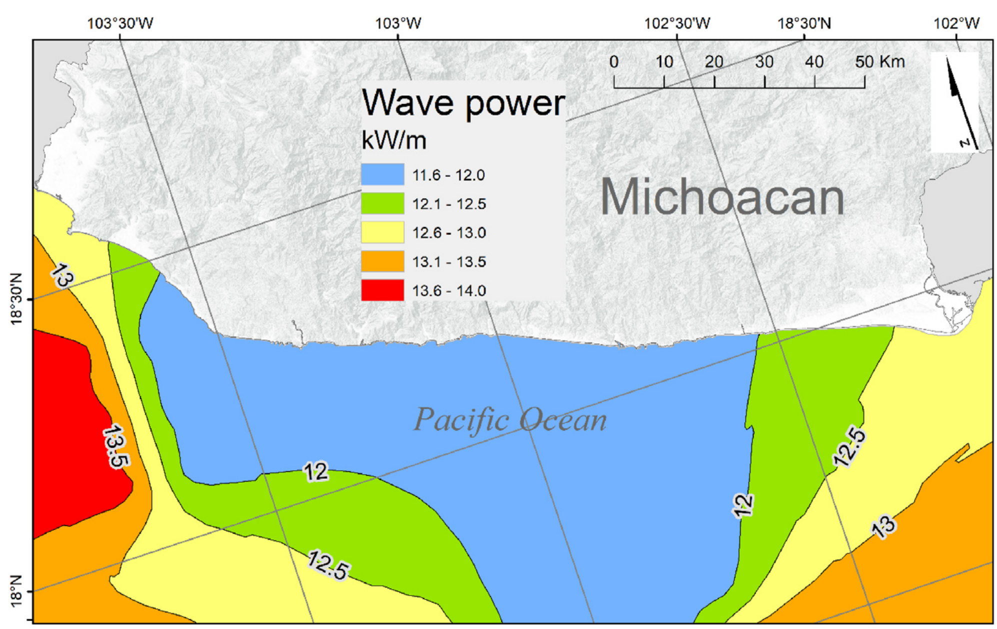

Fig. 9. Average wave power (in kW/m) for 2008 to 2018 off the coast of Michoacan.

there are no terrestrial natural protected areas. Offshore, the Deep Mexican Pacific protected area should be avoided. Additionally, care should be taken around the two protected beaches (Playa Maruata and Colola and Playa Mexiquillo) as well as the Caiman lagoon (see Fig. 7). To our knowledge, a systemic analysis of potential ocean energy production from a multidisciplinary approach (social, environmental and energetic) is seldom done, since most studies focus on one of these (Martínez et al. in revision). A handful of studies have explored ocean energy production from different perspectives. For instance, Mendoza et al. (2019) recommend a theoretical framework to evaluate the potential environmental impact of ocean energy devices, while considering how these devices work and their potential socioeconomic impacts. In turn, Felix et al. (2019) analysed the technical, environmental, and social challenges of ocean energy production in tropical regions. These approaches are certainly innovative and interesting, and provide a theoretical framework that should be considered. Nevertheless, unlike the above-mentioned studies, in this case we also followed a systemic approach geographically focused on a coastal region to explore the feasibility of developing alternative energy production.

The theoretical estimations of ocean energy resources showed that there is insufficient energy available from ocean currents in the study area. Therefore, conversion projects of this type are not viable here. On the other hand, energy from waves and thermal gradients

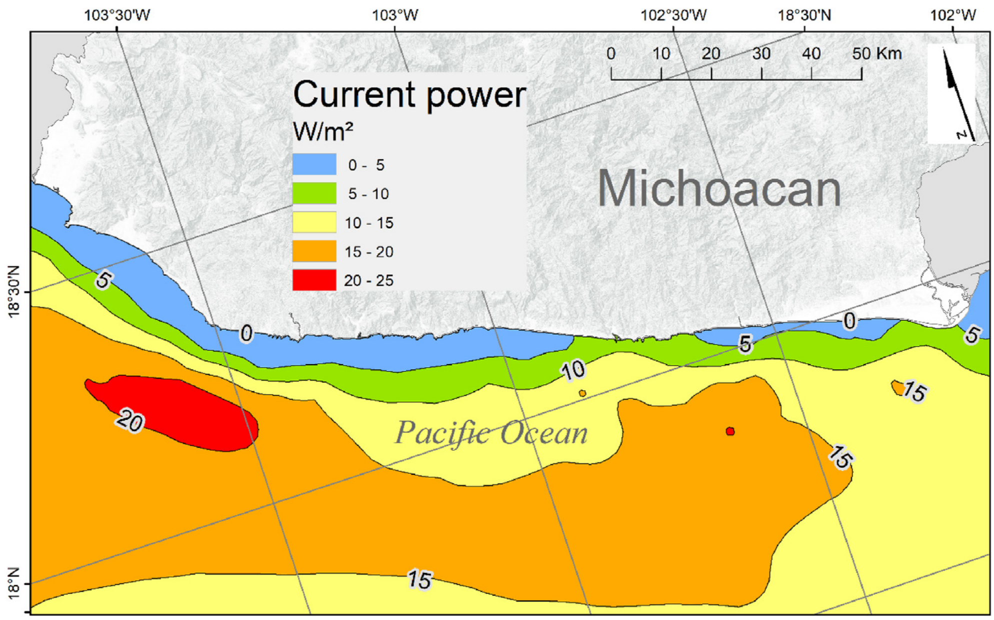

Fig. 10. Average current power (in W/m^2) for 2008 to 2018 off the coast of Michoacan.

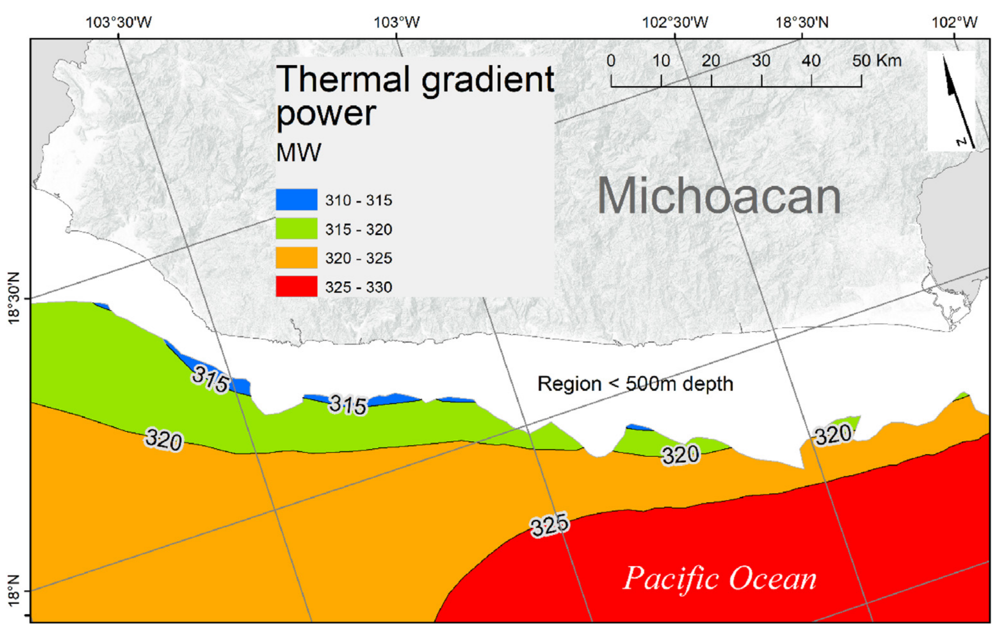

Fig. 11. Average thermal gradient power (in MW) for 2008 to 2018 off the coast of Michoacan (water depth >500 m).

meet a minimum criteria to start the operation of energy converter devices. There is a persistent minimum of ~2 kW/m of wave energy, which may be enough to deploy some wave energy converters, at least for low-energy production. Some alternatives are the point absorber devices, in which the required mean wave power range for operation is between 3.4 and 80 kW/m and 2.8–40 kW/m for floating and fixed configuration, respectively (Mustapa et al., 2017). Some of these devices, rated below 1000 kW capacity, are the WaveBob (Weber et al., 2009), Ceto (Mann, 2011) and SeabasedAB (Chatzigiannakou et al., 2017) models, whose prototypes have lengths of ~20, ~7 and ~3 m, respectively (Mustapa et al., 2017).

In turn, thermal gradient energy, showed that the minimum requirement to install an Ocean Thermal Energy Conversion (OTEC) plant is attained at 500 m depth, some kilometers off the coast. Alternatives for viable projects would be small fixed plants close to the shore, since design concepts for floating plants are still being developed (Adiputra et al., 2020; Rivas et al., 2016).

From the GIS socioeconomic and environmental analysis, two prospective regions, near the cities of Coahuayana and Lazaro Cardenas, were identified as having potential (Fig. 13). The development of energy conversion projects in these areas should avoid affecting Natural Protected Areas, benefit isolated communities, prevent the alteration of traditions of indigenous communities, take advantage of the coastal infrastructure (e.g., ports and substations), and minimize interference to fishing activities.

The EIA (2020) reported that in 2019, the average Levelised Cost

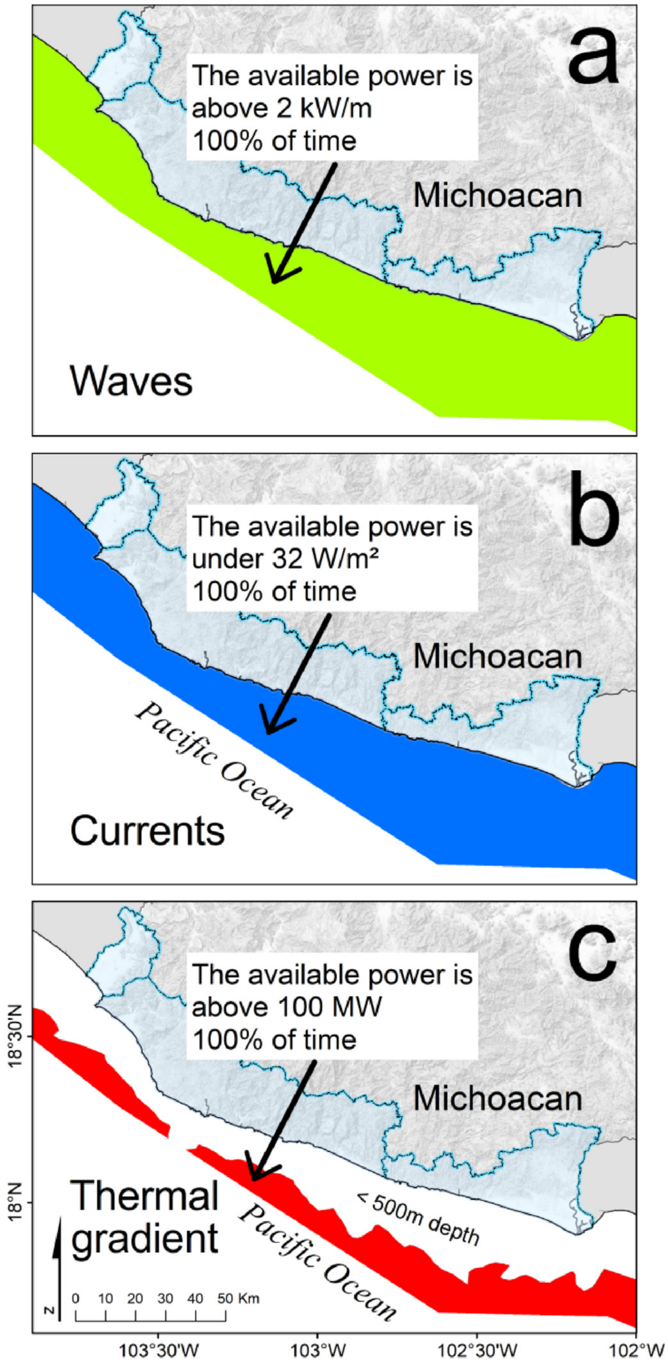

Fig. 12. Availability of ocean energy resources in the study region that was defined after considering the ambiental restrictions. (a) Wave power. (b) Current power. (c) Offshore thermal gradient power.

of Energy (LCOE), in USD per MWh, for USA were: Ultra-supercritical coal (72.81), Combined cycle (42.89), Advanced nuclear (69.37), Geothermal (35.56), Biomass (86.83), Wind onshore (35.97), Wind offshore (85.53), Solar photovoltaic (27.71) and Hydroelectric (53.58). Chozas (2015) reported significantly higher LCOE (in USD per MWh) for ocean energy, as: wave (120–470), tidal (130–280) and OTEC (150–280). As the technologies to harness ocean energy are still maturing technologically, their LCOE are significantly higher than other renewable and conventional technologies. However, there are good signs, Lamy and Azevedo (2018) and OEE (2016) point out that with the momentum that technologies are taking to harness ocean energy, their LCOE will decrease significantly in the coming decades, bringing competitive costs. Furthermore, there are estimates that by 2050, around 7% of the total global electricity production could come from ocean areas (Esteban and Leary, 2012). Other aspects to consider, as for any type of technology, are that the LCOE depends on the available resource, its location, local infrastructure, dispersion of consumption centers, to mention only some facts that determine the LCOE (de Andres et al., 2017). Currently, the LCOE in some parts of Mexico is up to 163 USD per MWh (CENACE, 2018). And finally, there are people who do not have access to electricity because they live in places of difficult access, which makes their connection to the electricity grid unfeasible.

4.1. Social perception

It is important to point out that although the criterion of social perception is not being considered in this study for an initial approach, we consider it relevant, and also necessary to be taken into account before intervening in a region. Indeed, local perception and acceptance of technological changes, and their installation in a specific area, can be a challenge for renewable energy projects (Wüstenhagen et al., 2007). Studies in Mexico and other countries show the difficulties that these projects face when there is a negative perception on the part of the people there. These perceptions are not necessarily due to a general rejection of renewable energy, but in many cases it is because of local environmental concerns (Delgado, 2016; Necefer et al., 2015; Vélez, 2017), as well as economic (Caballero, 2013; Valdivieso, 2012), political (González and Estévez, 2005) and cultural (Delgado, 2016; Lamy et al., 2020; Vélez, 2017) reasons. It has been seen that one common denominator in such opposition is the lack of attention paid to the particularities of each case (Ek, 2005; Wolsink, 1999).

There are already several examples that demonstrate the importance of considering each case specifically. When it comes to real, concrete projects opposition can grow considerably (Krohn and Damborg, 1999). So, once defined in coarse terms (physical and socio-environmental data), if a territory has initial (potential) conditions for the development of a harnessing ocean energy project, it would have to go to a phase of finer analysis, where the opinion of the local population on the specific project is taken into account.

Previous studies with wind farm generated electricity in the Tehuantepec Isthmus, in Oaxaca showed intense opposition to new renewable energies. Here, native indigenous communities did not accept the wind farm devices because of loss of their natural and cultural patrimony (Delgado, 2016; Vélez, 2017). The consequent social conflict became so complex and intense that the Supreme Court of Justice, found in favor of the indigenous groups, in some cases, and cancelled some of the wind-farms (Olvera, 2018). Similar opposition to wind energy farms has occurred elsewhere in Mexico (Cozumel) (Valdivieso, 2012; Caballero, 2013), and in England. In fact, the British government recognized such controversy as one of the barriers in the fight against Climate Change (Devine-Wright, 2005). In Spain, an ocean energy project in the Sea of Trafalgar was cancelled due to the population's mistrust of the project developers and a lack of clarity, from the government, in the communication and decision-making processes (González and Estévez, 2005).

Therefore, care should be taken to prevent such social problems before promoting ocean energy generation, because the local sea scapes, natural features and cultural heritage, as well as economic characteristics may be altered significantly (Devine-Wright, 2005; Lamy et al., 2020; Necefer et al., 2015; Wüstenhagen et al., 2007). Preliminary studies are necessary to determine to what degree the

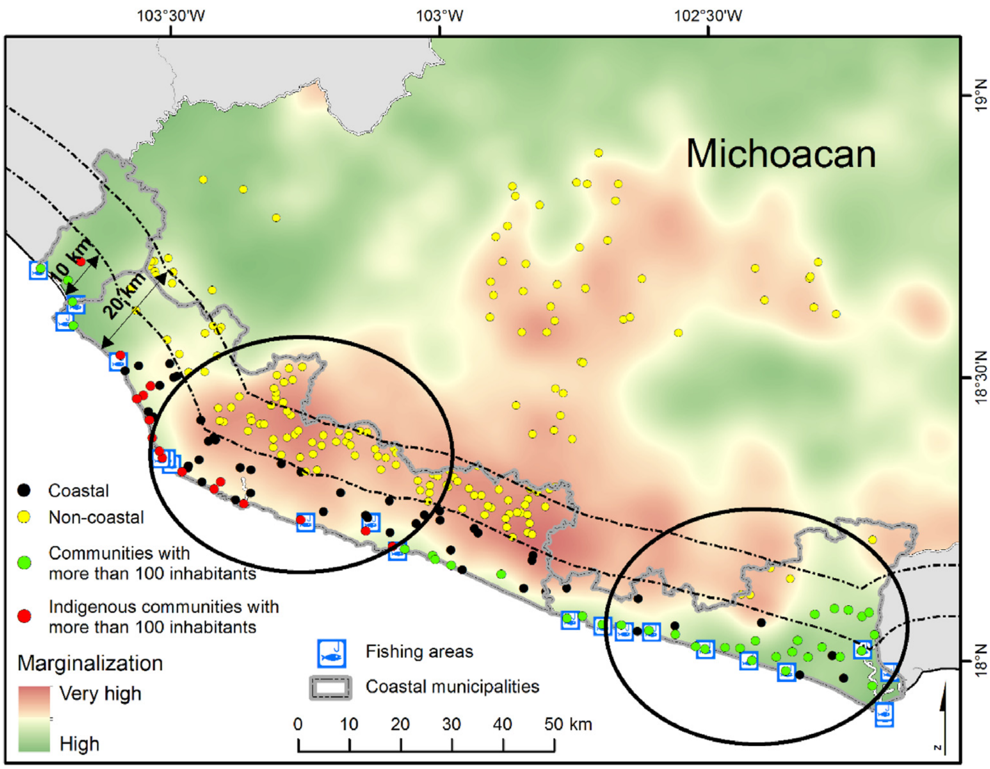

Fig. 13. Location of the two areas where ocean energy could be developed, based on energy potentials and socio-economic and environmental features.

local communities agree with such development (González and Estévez, 2005). Whether indigenous or not, the cosmogonic perspective of local inhabitants regarding their environment and new technologies should always be respected (SENER-BID, 2016). Therefore, a more detailed study of the social perception towards new energies is certainly necessary.

5. Conclusions

Ocean energy resources can be an alternative to fossil fuels, either on a large scale in regions with high availability of resources, or at smaller scale, providing basic power needs to populations located in coastal regions. Such alternative energy production should be socioeconomically viable and environmentally adequate, so that it really becomes a green and sustainable option. These topics have been discussed in the literature to provide guidelines for the implementation of some types of renewable energies in isolated communities in developing countries; however, so far, this has not been done for different types of ocean energy. To contribute to this, this paper considers socio-economic and environmental factors when verifying the possibilities of ocean energy extraction in remote communities, along the coast of Michoacan, (south-western Mexico) which do not have electric power. We identified prospective localities where developing ocean energy production is viable and sustainable, based on the location and needs of the human settlements there. Environmental restrictions were considered and the most effective energy types were analysed, using theoretical approaches. With this, we determined, from a qualitative point of view, potential sites and locations for ocean energy provision according to energy type, distance from the ocean, as well as social needs and environmental restrictions. A multi-disciplinary approach is effective here, since it helps in the decision-making process of where to best locate ocean energy devices.

The approach described in this study could be extended to evaluate prospective areas in other developing regions using GIS analyses, and including restrictive factors, as required. It is hoped that this research will serve as a practical guideline to the evaluation of other regions of Mexico, and countries with similar challenges, including the different constraints when necessary. As a next step to extend the theoretical estimation of ocean energy resources, further research should be performed to carry out technical and practical assessments, including the economic feasibility of grid and off-grid projects. In addition, on site, field observations are largely missing, and are necessary to assess the potential environmental impact of ocean energy devices. Local studies to determine the perception and acceptability of the local communities towards new technologies in their lands are also necessary, so that local inhabitans may participate in decision about implementing new technologies in their area. As has been shown for other types of renewable energies, off-grid ocean energy projects could provide isolated communities, with electricity, at least to satisfy basic necessities. Finally it is important to acknowledge that besides the technical, environmental and social elements, the projects must be economically feasible as well, as has been clearly stated by (Lamy and Azevedo, 2018), among others.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Jassiel V. Hernández-Fontes: Conceptualization, Methodology, Writing - review & editing. **M. Luisa Martínez:** Conceptualization, Methodology, Writing - review & editing. **Astrid Wojtarowski:**

Methodology, Data curation, Investigation. **José Luis González-Mendoza:** Software, Data curation, Investigation. **Rosario Landgrave:** Methodology, Software, Data curation, Visualization, Investigation. **Rodolfo Silva:** Conceptualization, Methodology, Resources, Writing - review & editing.

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