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Assessment of marine energy-biotopes for Cozumel Island's reefs: A resource for tourism and renewable ocean energy

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ABSTRACT

In general, ocean energy refers to renewable energy for human consumption, but less often relates to conservation and environmental protection. Within this context, this study describes and investigates energy-biotopes as a new concept, based on energy features, to use as a relevant resource for reefs conservation, marine-based tourism, and the harvesting of renewable ocean energy for Cozumel Island. Cluster analyses and linear trend models indicate an energy-tourism-economy connection with a similarity >90% and a correlation >0.976 between tourist arrivals, total revenue (US$ 161.74), and electric energy consumption (~64.62 Wh), per tourist. Moreover, field measurements of ocean current velocities (U) were conducted to assess the spatial distribution of kinetic energy density (E_D) over the western coast of Cozumel Island. These results were compared with information obtained from prior studies on reef cover, benthic distribution, and tourism activities to identify the environment-energy-tourism relationship. Results indicate that marine biotopes with low and intermediate energy values ($E_D < 60$ J/m^3, $U < 0.34$ m/s) correlate with reef structures that are highly attractive for tourism and with moderate flow velocities for drift-diving, which represents the basis of tourism and the primary source of income for Cozumel Island. In contrast, high-energy biotopes ($E_D > 250$ J/m^3, $U < 0.70$ m/s) may contribute to meeting energy demands through the use of marine energy and the resulting increase in tourism and economic development in the area. However, the effects on marine organisms that are not typically attractive for tourists, but are of ecological significance, should be considered. Environmental habitats and electric energy demands are discussed regarding the local economy, which supports a floating population of 4.10 million people and where the reef environment plays an essential role both as part of the marine landscape and in the formation of globally unique energy-biotopes.

1. Introduction

Coastal and marine-based tourism represent a large sector of several countries in the Caribbean economy. Moreover, the Caribbean is a world-leading region for cruise tourism that has developed since the second half of the 20th century (Lawton and Butler, 1987). With more than 23 million cruise ship passengers and an expenditure of US$ 2.45 billion by 2015 (ACS-AEC, 2016; FCCA, 2018), the main activities in the coastal zone center around the diversity and richness of natural habitats, clear and attractive water, beaches, and reef formations (Fang and Dakui, 2014; Kurniawan et al., 2016). Hence, establishing an economic framework for tourism in developing countries, particularly for islands and remote locations, has become a top priority (Dogru et al., 2020; Gössling, 2000; Seetanah, 2011), as they encompass the most economically valuable reefs, globally (Patil et al., 2016).

The increase in mass tourism poses resource challenges for vulnerable and fragile environments (Mcelroy, 2003; Wilkinson, 2012) and affects the protection of marine resources (Allen, 1992). Tourism contributes to global environmental changes by altering the natural fluxes of energy as well as the social perception and understanding of the environment (Gössling, 2002). In this regard, energy is among the critical factors concerning accessibility, demand, and an environmental dimension for sustainability (Vera and Langlois, 2007). The introduction of local wind power and solar energy generating systems and, recently, the harvesting of ocean energy in remote areas (i.e., islands or isolated coastal regions), are essential contributions to the generation of a

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sustainable renewable energy-based system (Graziano et al., 2017; Jenniches, 2018) and a reduced dependency on weak electricity grid connections (Duić and da Graça Carvalho, 2004). However, ocean energy has primarily been investigated from a productivity perspective, focusing on the generation and extraction of the energy, without first assessing energy conditions as critical components for the environment and its development. Therefore, on-site environmental impacts should be established before the development of activities that have a high consumption of renewable energy (Hammar et al., 2017), as local systems and livelihoods may experience a wide array of changes caused by such activities (Dorotić et al., 2019).

The benthic habitats are closely related to marine hydrodynamics and energy fluxes (Herkül et al., 2016), as well as to the marine-based tourism activities and the current interest in marine renewables to meet the energy demands of increasing tourism. In the Mexican Caribbean, a number of sites around Cozumel Island have been identified as suitable for the production of marine energy from ocean currents generated by the ocean global circulation, including sites with flow speeds of up to 1.6 m/s (Athié et al., 2011; Carrillo et al., 2015; Martínez et al., 2019). At the same time, ecosystems of coral reefs, mangroves, beaches, and seagrass beds are important for tourism (Aquing et al., 2007). However, the relationship between the environmental conditions of zones that are suitable for the harvesting of renewable ocean energy in Cozumel Island (Alcérreca-Huerta et al., 2019a, 2019b) and tourism activities has not yet been investigated. Furthermore, direct observations of marine energy resources as well as data related to links between the benthic environment, ecological impacts, and limitations of energy extraction, are scarce (Bonar et al., 2015; Henkel et al., 2014).

This study aims to identify marine energy biotopes in Cozumel Island developing a new way to describe biotopes based on energy, a vital attribute of the environment, to characterize relevant resources for reefs, marine-based tourism development, and the harvesting of renewable ocean energy. For this purpose, analyses and measurements were conducted to assess the following: i) the increase in tourism, electric energy demand, and exponential population growth (1997–2017) as socioeconomic drivers of environmental pressure; ii) the spatial distribution of marine kinetic energy density available at the different biotopes along the western coast of Cozumel Island, and iii) the link between the marine kinetic energy, environmental features (e.g., reef height/cover, benthic profile distribution), tourism, and infrastructure development. The approach of considering marine energy biotopes might be used to face integrated ocean and coastal management problems, where it is required the understanding of the spatial marine energy resource distribution, its relationship with the environment, and in a context of a place with high tourism activity, such as the marine spatial planning for defining optimal areas of marine energy harvesting by reducing possible impacts on reefs conservation and the existing marine-based tourism development.

2. Methods

2.1. Study area

Located in the Mexican Caribbean, Cozumel Island lies approximately 20 km east off the coastline of the Yucatan Peninsula (Fig. 1). The island is 48 km long and 14.8 km wide, covering an area of 647 km^2. The

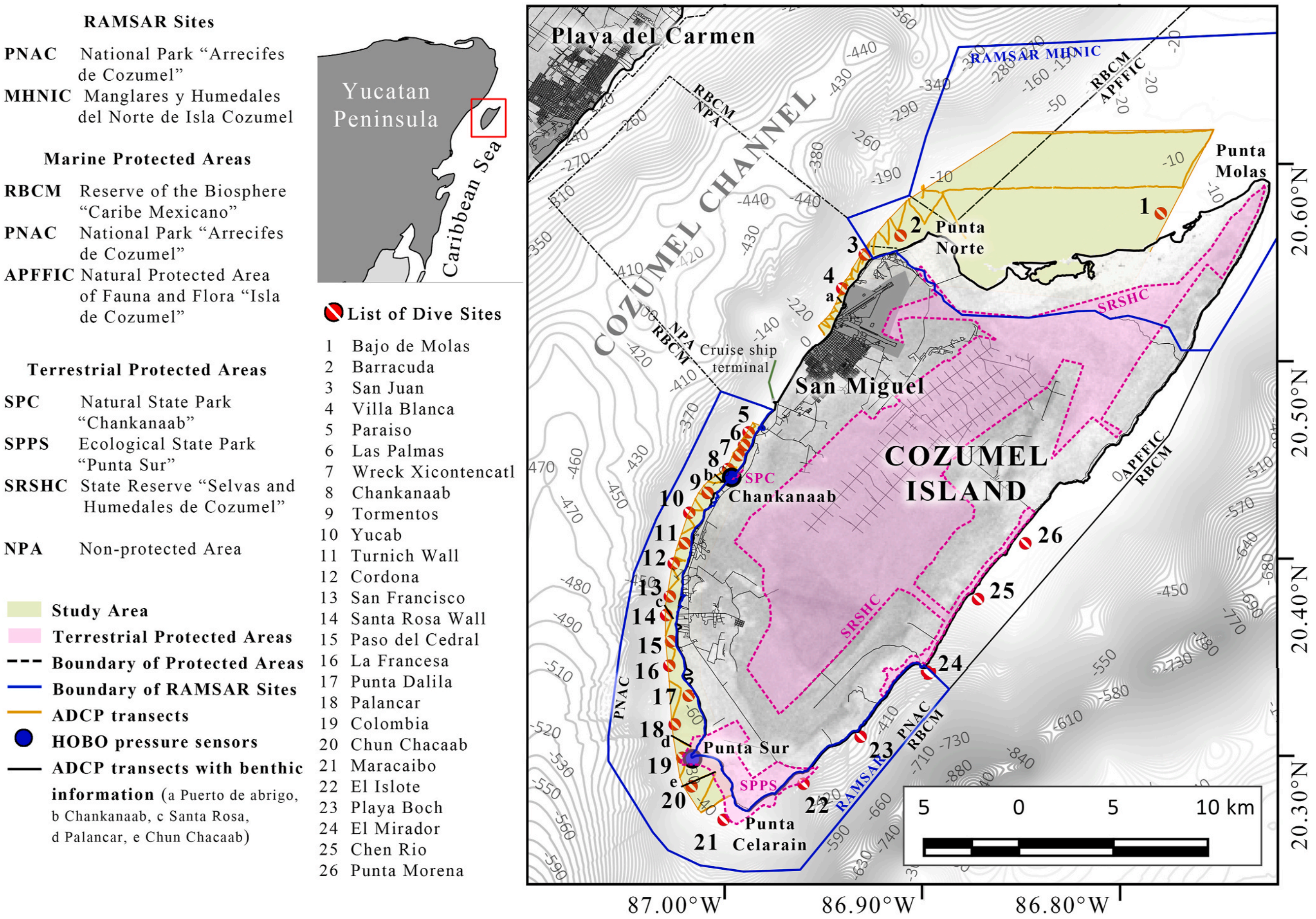

Fig. 1. Location of the study area around the western and northern coastal shallow waters of Cozumel Island, including ADCP transects, HOBO sensors used for field measurements (September 23–29, 2018), as well as the boundaries of RAMSAR sites, natural protected areas, dive sites, and population settlements.

passageway between the mainland and Cozumel Island forms the Cozumel Channel that is approximately 50 km long, 18 km wide, and of varying depths up to 500 m. A flow volume deviation of 5 Sv (Mm^3/s) from the mean transport of the Yucatan Current (Chávez et al., 2003) throughout the Cozumel Channel results in average surface speeds of up to 1.2 m/s (Cetina et al., 2006). The almost uniform and continuous kinetic energy flux from the ocean current is the main driving force within the Cozumel Channel, recently explored as a potential marine energy resource to meet the island's increasing energy demands (Alcérreca-Huerta et al., 2019a, 2019b).

Discontinuous coral reef formations around Cozumel Island cover a total area of approximately 17 km^2 along a narrow, insular shelf (300–500 m) with shallow waters reaching depths of 35–50 m (Gallrein and Smith, 2003; Jordan-Dahlgren, 2007; Jordan-Dahlgren and Rodriguez-Martinez, 2003). Over the last three decades, the following marine and terrestrial areas, as well as RAMSAR sites, have been declared protected areas (Fig. 1) (DOF, 2016; 2012; 1996; RAMSAR, 2019; Red Nacional de Sistemas Estatales, 2018): PNAC-National Park "Arrecifes de Cozumel" (11988 ha) on the southwest coast of Cozumel Island comprising coral reef systems and mangrove wetlands; MHNIC-"Manglares y Humedales del Norte de Isla Cozumel" designated as a RAMSAR site due to the mangrove systems; RBCM- Reserve of the Biosphere "Caribe Mexicano", declared in 2016 as a marine zone for the conservation of its biodiversity; APFFIC-Natural Protected Area of Fauna and Flora "Isla de Cozumel" on the north and northeast coast of Cozumel (37829 ha), partly within the boundary of the MHNIC; SPC- Natural State Park "Laguna de Chankanaab" (14 ha); SPPS-Ecological State Park "Punta Sur" (1130 ha); and SRSHC-State Reserve "Selvas y Humedales de Cozumel" (19846 ha). Particularly, the RAMSAR sites stands due to the coastal wetlands in Cozumel with mangrove systems recognized of international importance. Moreover, Cozumel is a member of the UNESCO World Network of Biosphere Reserves (WNBR) within the Man and Biosphere (MAB) program, due to current developments around marine-based tourism activities and cruise destinations. Hence, Cozumel aims to be an inclusive, safe, resilient, and sustainable destination (SEDATU, 2016), built upon a balanced, scientifically based relationship between people and nature (UNESCO, 2017).

The natural beauty of Cozumel Island, together with its remarkable archaeological vestiges from the Mayan culture, represents a tourism asset for economic development since the 1960s (Lawton and Butler, 1987). Estimations account for 1500 daily visitors to the reef systems in the marine protected areas (SEMARNAP, 1998). According to Mota and Frausto (2014), 41% of tourists in Cozumel Island are drawn by its focus on water activities, with scuba diving and snorkeling (Fig. 1) being the main economic activities that sustain the region. Moreover, Cozumel is part of the Great Mayan Reef and, because of ocean currents along with its insular shelf, Cozumel is known as the drift-diving capital of the Caribbean Sea (Mota and Frausto, 2014; Santander-Botello and Propin-Frejomil, 2009).

Cruise tourism plays a critical role in the economy of Cozumel, which, in turn, has catapulted the development of marine-based tourism. Port infrastructure, developed as part of government policies in the 1990s, strengthened the capacity for receiving mass tourism and placed Cozumel among the leading national and international cruise destinations (Palafox-Muñoz and Segrado-Pavón, 2008; Palafox-Muñoz and Zizumbo-Villarreal, 2009). The piers of Cozumel, between San Miguel and Chankanaab, can receive up to seven simultaneous cruise ship arrivals, in addition to those piers developed for cargo and passengers transportation between the island and the mainland (Martínez, 2012). Tourism infrastructure within the island is represented by 66 lodging locations, as well as 480 commercial food and beverage establishments, and 27 car rental companies, for approximately 5638000 tourists by 2019 (SEDETUR, 2020).

2.2. Field measurements, sampling techniques, and data analysis

In this study, population growth, electric energy consumption, and tourist arrivals were analyzed for Cozumel Island considering cluster, trend, and regression analyses performed in R Statistical Software, to estimate electrical energy demand of the island as a function of tourism development, and of the economy. The analyses aim to investigate drivers of pressure on reef systems and the current need to satisfy increasing electric energy demands of tourism over the last decade. Databases of electric energy consumption (INEGI, 2018; SENER-World Bank-ESMAP, 2015), cruise tourist numbers (ACS-AEC, 2016; Palafox-Muñoz and Segrado-Pavón, 2008; SCT, 2004; SEDETUR, 2018), and economic revenue (Palafox-Muñoz and Segrado-Pavón, 2008; SEDETUR, 2018) were considered for this purpose.

Analyses also included the spatial variation of the kinetic ocean energy resource around Cozumel Island. Instantaneous water velocities were measured during field surveys (September 21–29, 2018) using a ship-mounted acoustic Doppler current profiler (ADCP) (Teledyne RDI RiverPro, 1 MHz) equipped with a fully integrated GPS. Furthermore, ADCP transects were defined over the western and northern insular shelf of Cozumel Island at water depths <35 m, covering a total surveyed distance of 62.3 km and an area of ~130 km^2 (Fig. 1). Due to the area extent, transects were conducted once over the study area and no temporal flow variabilities were accounted. The spacing between transects was of 2 km from Punta Sur to Chankanaab, and about 0.5–1.0 km close to Punta Norte, where increasing flow velocities were identified and the effect of the ocean current over the insular shelf of Cozumel Island intensifies rapidly. Velocity profiles along transects were measured considering a vertical bin size of 0.5 m and a sampling output rate of 2 Hz, leading to a spatial resolution of 0.5–1.0 m between vertical profiles (pings) in a transect. Bottom tracking mode was used, thus true velocities magnitudes were estimated by subtracting the boat's velocity from the relative water velocity measured by the ADCP.

The depth-averaged velocity magnitude ($V_{Av,Mag}$) of each velocity profile within a transect was then used to estimate a depth-averaged energy density value (E_D). The depth-averaged velocity magnitude considered the velocity magnitudes given by the bins in the profile. As each profile measured was georeferenced, a depth-averaged velocity magnitude ($V_{Av,Mag}$) associated to a specific georeferenced position was obtained. The value of $V_{Av,Mag}$ was used to estimate E_D, defined as the amount of energy per unit volume of water and calculated as $E_D = 0.5\rho (V_{Av,Mag})^2$, with E_D measured in J/m^3 ($1\ J/m^3 = 2.78 \times 10^{-4}\ Wh/m^3$), with $V_{Av,Mag}$ in m/s and ρ as water density in kg/m^3. Water density values were derived from measured temperature and salinity profiles obtained with a CTD profiler (YSI CastAway). Spatial linear interpolation was performed considering E_D values at each profile and their georeferenced location, resulting in a spatial distribution map of depth-averaged energy density over the insular west shelf of Cozumel. The ADCP measurements were complemented with bathymetric data from a GPS-Humminbird 899 CXI HD SI echosounder.

The relationship between the natural environment and the calculated kinetic ocean energy resource was investigated through the comparison of obtained energy density data and information gathered from existing studies describing reef cover, structure height, and benthic distribution.

The depth-averaged energy density map for the insular shelf of Cozumel was compared to the reef structure described in ASK (2017) that includes the following three categories of coral cover and reef structure height: a) low developed reef structure describing coral cover of 0–15% with small coral mounds and coral structures heights of up to 3.0 m; b) well developed reef structure featuring coral cover of 15–35% and reef structure heights ranging from 0.5 to 7.0 m; and c) highly developed reef structure with coral cover of >35% and structures ranging from 1.5 to more than 7.0 m in height.

Energy density profiles along five selected transects, distributed along the west coast of Cozumel (Fig. 1), were superimposed on coincident existing profiles with detailed benthic distribution provided in Muckelbauer (1990). Marine energy-biotopes were identified in terms of the kinetic energy density using the following conditions: a) high-energy biotopes with flow velocities >0.7 m/s ($E_D > 250$ J/m^3), where harvesting of marine kinetic energy is feasible through recently designed marine turbines (Alcérreca-Huerta et al., 2019b; Encarnacion and Johnstone, 2018); b) intermediate-energy biotopes with values between the median of the energy density dataset and the feasibility velocity for energy harvesting (i.e., velocities ranging from 0.20 to 0.70 m/s ($20 < E_D < 250$ J/m^3)); and c) low-energy biotopes, defined by velocities < 0.20 m/s ($E_D < 20$ J/m^3). It was decided to divide the intermediate-energy biotope into high-intermediate (i.e., $60 < E_D < 250$ J/m^3) and low-intermediate (i.e., $20 < E_D < 60$ J/m^3) energy, with a limit of $E_D = 60$ J/m^3 within the third quartile (Q3) of the energy density dataset. The intention of this separation was to present a more accurate description of the transition of biotopes between low and high-energy, where there are differences between seaweed and corals families.

As a result, marine energy-biotopes are based on their energy flow conditions, the existence and profile formations of benthic organisms, as well as leading tourism activities and/or infrastructure of Cozumel Island described in Barranco et al. (2016), Gallrein and Smith (2003), and Martínez (2008).

3. Results

3.1. Energy, population, and tourism growth

The second half of the 20th century has witnessed the development of population settlements on both sides of the Cozumel Channel (Fig. 1). San Miguel de Cozumel and Playa del Carmen grew from being fishing villages with 5860 and 1270 inhabitants in 1970 to becoming globally renowned tourist destinations with 84519 and 304942 inhabitants by 2020, respectively (INEGI, 2021). Between 2005 and 2010, the annual rate of population growth was 0.86% for Cozumel Island and 4.93% for Playa del Carmen. However, both Cozumel and Playa del Carmen present maximum annual growth rates of up to 22.5% (1970–1980) and 130.8% (1990–2000), respectively.

An electric energy consumption of 2749 kWh/capita was recorded in 2013 for Cozumel, considering a population of 86751 inhabitants and an annual consumption of 238.51 GWh in the same year. In this regard, electric energy consumption in Cozumel was 32.2% higher than the national use of 2079 kWh/capita (IEA, 2019). Furthermore, using the information provided by SENER-World Bank-ESMAP (2015), a comparison of the electric energy consumption of Cozumel and cities with similar tropical climate conditions (Fig. 2) shows that the electric energy consumption of Cozumel was 14.7, 33.4, and 223% below that of Durban, Kuala Lumpur, and Singapore, respectively. On the other hand, Cozumel exceeded the electric energy consumption per capita of cities such as Rio de Janeiro, Bangkok, and Colombo with 6.47, 8.31, and 0.75 million inhabitants and 2206, 2157, and 1718 kWh/capita, respectively (Fig. 2).

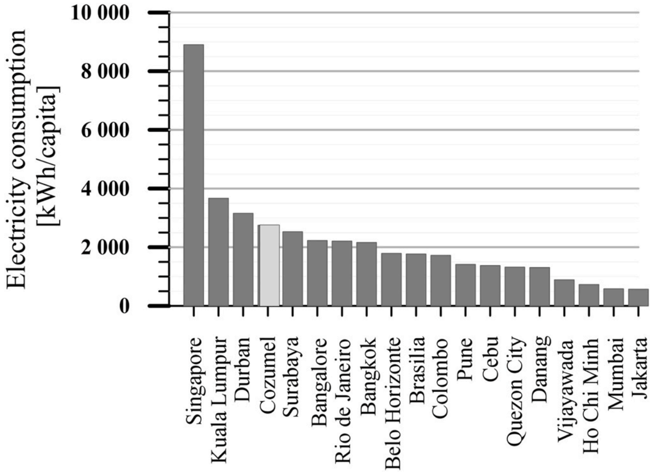

Fig. 2. Comparison of electric energy consumption between cities with tropical weather including Cozumel Island (modified from SENER-World Bank-ESMAP (2015)).

The increasing trend of tourism and population growth contribute to an overall pressure on the electric energy supply required for Cozumel Island (Table 1). In 2017, 4.838 million annual tourist arrivals were recorded on Cozumel, bringing in a substantial revenue of US$ 762 million, of which the total electric energy expenditure was close to US$ 30 million.

Tourist arrival data for Cozumel indicate an upward trend (Fig. 3a) from nearly 1.9 to a staggering 4.8 million arrivals per year (i.e., an average annual increase of 161780 arrivals), with an average increase of 8.7% from 1997 to 2017 (Table 1). The total number of arrivals indicates that cruise tourism represents the primary economic sector of the island, with an increase from 78.1% in 2000 to 84.7% in 2017, reaching a maximum of 89.1% in 2003. Furthermore, in the last two decades (1997–2017), cruise ship passengers represented 73.5–89.1% of total tourist arrivals, showing 3.76 times increase from 1.088 to 4.098 million arrivals. For the same period, revenue increased from US$ 327.1–762.6 million (i.e., nearly 2.33 times), whereas electric energy consumption increased 1.65 times (Table 1).

Cozumel represents 6.62% of the state average electricity consumption, and 11.7% of the tourism state revenue. Furthermore, tourism revenue represents 4.41% of the national income from tourism in Mexico (N-L ratio, Table 1). The highest contribution occurred from 1998 to 2008, after which a continuous reduction occurred. Lower values and percentages of the state local electric energy consumption (S-L ratio, Table 1) occurred for 2004–2006, possibly related to the effects of Hurricane Wilma in 2004 (Bardi et al., 2007; Ritchie et al., 2010; Scott et al., 2009).

Results from a cluster analysis indicate tourist arrivals, tourism revenue, and electric energy consumption of Cozumel Island to have similarities of over 90% (Fig. 3b). Furthermore, total tourist arrivals and electrical energy consumption for Cozumel show a similarity of 93.7%, further related to a similarity of 91.3% with tourism revenue. However, these variables do not present a correlation with hotel rooms, as a similarity of only 34.4% was recorded. Furthermore, an annual average of 4092 hotel rooms was recorded, with slight temporal variations throughout the years, remaining constant from 2010 to 2015. Despite the existing hotel infrastructure, tourism revenue and electric energy consumption were closely related to tourist arrivals, primarily cruise ship passengers.

Based on the previous results, the correlation between tourist arrivals and both revenue and electric energy consumption was analyzed (Fig. 3c and d). Trend-linear models of the form $y = mx$ were obtained through the regression analysis considering the data points in Fig. 3c and d, thus leading to eq. (1) and eq. (2) with correlation coefficients of $r_1 = 0.996$ and $r_2 = 0.988$, respectively:

$$CR = 161.74 \ (TA) \tag{eq. 1}$$

$$EEC = 64.62 \ (TA) \tag{eq. 2}$$

Cozumel revenue (CR) was given in US million dollars (MUSD) per year, tourist arrivals (TA) in millions per year, and electric energy consumption (EEC) in GWh/year.

According to eq. (1), each tourist arrival represented 161.74 USD of revenue for Cozumel, a rate that is almost constant from 2006 to 2017. Moreover, each tourist arrival represented an electric energy consumption of 64.62 Wh/tourist (eq. (2)). This result may better represent electric energy consumption demands from a floating population rather than the data produced only considering the local community.

Table 1
Electric energy consumption, tourist arrivals, and tourism revenue of Cozumel Island and comparison with national and state data.

Year	Electric energy consumption			Tourism			Revenues from tourism activities			
	State [GWh]	Cozumel [GWh]	[a]S-L ratio [%]	Tourist arrivals [mill./yr]	Cruise passengers [mill./yr]	Number of hotel rooms	National [MUSD[c]]	State [MUSD[c]]	Cozumel [MUSD[c]]	[b] N-L ratio [%]
1997	1431.40	ND	ND	ND	1.088	3618	7376.00	2707.80	327.10	4.43
1998	1562.60	ND	ND	ND	1.143	3798	7493.00	2943.80	398.30	5.32
1999	1669.36	ND	ND	ND	1.341	4357	7223.00	3250.60	320.10	4.43
2000	1996.04	165.64	8.30	1.926	1.505	3956	8294.00	4076.90	349.80	4.22
2001	2029.42	175.25	8.64	2.051	1.595	3956	8401.00	ND	ND	ND
2002	2356.14	172.08	7.30	2.727	2.343	4007	8858.00	ND	ND	ND
2003	2289.78	168.95	7.38	3.042	2.709	4010	9362.00	ND	ND	ND
2004	2459.57	135.34	5.50	3.281	2.862	3738	10797.00	ND	ND	ND
2005	2633.32	140.43	5.33	2.916	2.519	4205	11795.10	ND	ND	ND
2006	2772.76	157.22	5.67	2.798	2.351	4205	12176.60	3235.03	402.16	3.30
2007	3223.44	207.57	6.44	3.042	2.488	4373	12901.00	3319.08	501.72	3.89
2008	3542.48	230.47	6.51	3.494	2.569	4327	13289.00	4357.65	708.05	5.33
2009	3585.28	227.99	6.36	2.794	2.222	4355	11275.00	4137.32	505.55	4.48
2010	3624.71	222.75	6.15	3.435	2.908	4098	11872.00	3689.30	521.56	4.39
2011	3757.42	227.93	6.07	3.347	2.871	4098	11663.00	3872.50	511.53	4.39
2012	3881.06	ND	ND	3.191	2.745	4098	12720.17	4341.07	484.23	3.81
2013	4034.56	238.51	5.91	3.201	2.754	4098	14187.88	4954.36	485.96	3.43
2014	4219.01	255.67	6.06	3.990	3.405	4098	16258.47	5678.71	617.78	3.80
2015	4504.54	270.61	6.01	3.966	3.391	4098	17457.98	6248.88	611.20	3.50
2016	4764.66	274.75	5.77	4.356	3.637	3748	19570.81	6724.36	710.57	3.63
2017	4499.35	ND	ND	4.838	[a].098	4687	ND	6584.90	762.63	ND
Average	3087.47	204.45	6.62	2.951	2.502	4092	11648.55	4382.64	513.64	4.41

[a] n S-L ratio: proportion of the electric energy consumption in Cozumel Island compared to Quintana Roo State.
[b] N-L ratio: proportion of local revenue compared to national revenue.
[c] MUSD = US million dollars.

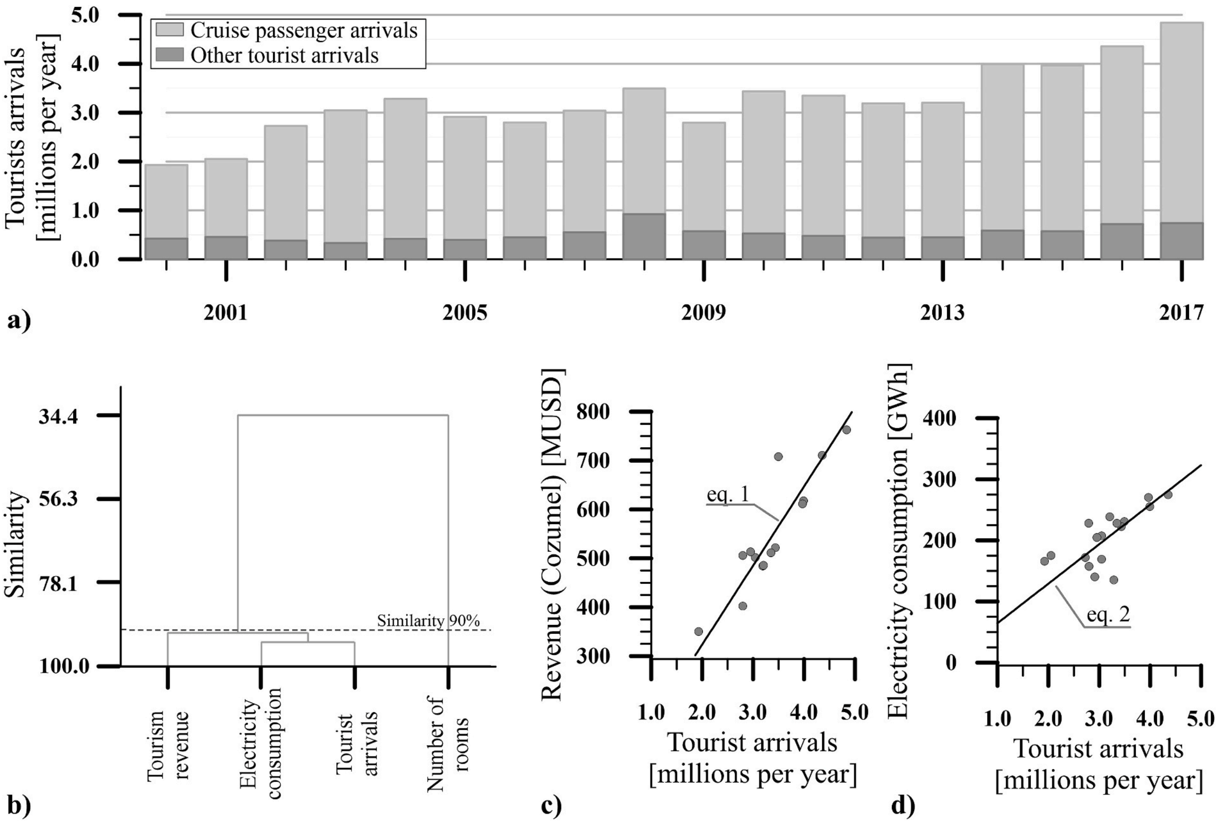

Fig. 3. (a) Annual tourist arrivals on Cozumel Island including cruise-ship and other arrivals, (b) dendrogram and similarity > 90% between tourism revenue, electricity consumption and tourist arrivals, (c) correlation analysis between tourist arrivals and revenue, and (d) electric energy consumption.

3.2. Ocean energy and reef environments: the marine energy-biotopes

The spatial distribution of the depth-averaged instantaneous energy density and reef structure, as described by ASK (2017), is presented in Fig. 4. Tourism-attractive sites recognized by specific reef structure or physical features around Cozumel Island are also depicted (e.g., reef-walls, diving and snorkeling areas).

Bands of high-energy-density ranging from 540 to 1260 J/m^3

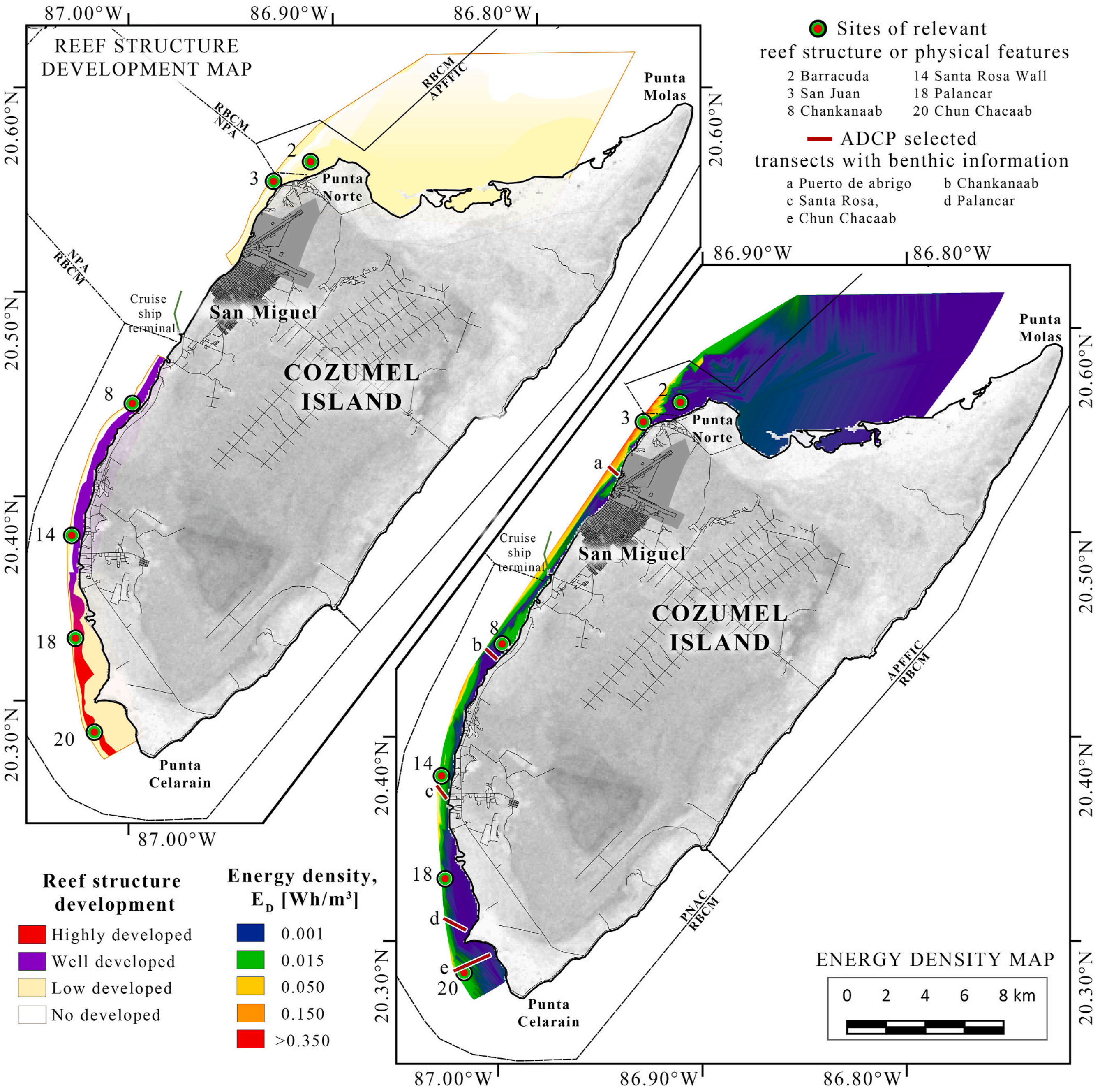

Fig. 4. Reef structure development (modified from ASK (2017)) and kinetic energy density maps around the western and northern coast of Cozumel Island including sites with significant reef structures or physical features.

(0.15–0.35 Wh/m^3) primarily lie parallel to the coastline, from near San Miguel (20.517° N) and increase northwards to latitude 20.573° N. The energy density corresponds to velocity with magnitudes higher than 1.0 m/s flowing in a northward direction and from 150 to 500 m off the coastline, at water depths of 10–35 m along the insular shelf edge limit. High-energy density also increases close to the shoreline at latitude 20.537° N, possibly due to the narrowing of the insular shelf near San Juan and Barracuda reefs. Notably, sites between San Miguel and San Juan are the most suitable for the harvesting of kinetic marine energy using low-speed velocity turbines (Alcérreca-Huerta et al., 2019a, 2019b).

Energy density values gradually decrease northwards beyond San Juan and Barracuda reefs, reaching values of 54 J/m^3 (0.015 Wh/m^3) over a strip bordering the insular shelf edge (Fig. 4). Further energy density bands range from 54 to 180 J/m^3 (0.015–0.050 Wh/m^3) due to 0.3–0.6 m/s velocities along the central and southern portion of Cozumel Island. The majority of Cozumel's resorts and dive sites (Fig. 1) are located in close proximity to these energy density bands (Fig. 4). Furthermore, several drift-diving hotspots (Fig. 1) that lie within these bands include well-developed reef structures such as the Santa Rosa Wall (coral formations over a wall with tunnels, overhangs, and caves), Palancar (5 km strip reef with coral formations over sandy bottoms), and Chun Chacaab (mildly sloping reef before the insular shelf edge) (Fig. 4). Areas with similar energy densities are also located near the shoreline, i.e., south of Cozumel airport, as well as between the cruise ship terminal pier and Chankanaab (Fig. 4). The energy density at Chankanaab relates to a southward flowing counter-current and a well-developed reef structure, as reported in (Alcérreca-Huerta et al., 2019b; Carrillo et al., 2012; Sandoval Vizcaíno, 2007). Further reports also describe outflows of cold freshwater from insular groundwater in Chankanaab (Carrillo et al., 2012; Gallrein and Smith, 2003; Yáñez-Mendoza et al., 2007) as well as the presence of reefs with crags, tunnels, caves, and crevices over the shallow platform (Gallrein and Smith, 2003; Sandoval Vizcaíno, 2007).

The northern area of Cozumel Island shows low energy density values of 3.6 J/m^3 (0.001 Wh/m^3), corresponding to flow velocities of 0.1 m/s (Fig. 4). In this zone, water depths vary smoothly between 0 and 20 m over a northward extension of the insular shelf, in contrast with the high energy density areas of the west coast where the shelf width is 0.5–1.0 km. Low energy density values occur along the length of the west coast of Cozumel from the shoreline to approximately 100 m seawards, with the exception of Chankanaab and San Miguel, with higher energy density values. Along the southwestern coast of Cozumel, between Palancar and Chun Chacaab, low energy density values are related to a terrace of shallow water (0–5 m) and a high reef structure located before the shelf edge, over which energy density gradually increases to 54 J/m^3 (0.015 Wh/m^3) (Fig. 4). Lower energy densities may be related to a decrease in flow velocity resulting from friction effects of shallow water and the shoreline.

Fig. 5 shows five selected transects in which calculated energy density profiles overlay the benthic distribution described by Muckelbauer (1990) to better describe the various energy-biotopes. The Puerto de Abrigo profile (between San Miguel city and San Juan reef, Fig. 4) depicts a high-energy density of $E_D > 250$ J/m^3 (0.069 Wh/m^3) over Rhodolite (red algae) seabeds and Xestospongia (sponge) structures. However, further Xestospongia and Rhodolite zones, as well as Syringodium (seagrass) beds also occur at high-intermediate energy densities $E_D > 120$ J/m^3 (0.033 Wh/m^3) over submarine terraces within the Santa Rosa, Chankanaab, and Chun Chacaab profiles (Fig. 5). Biotopes with high energy density conditions seem to be primarily related to underdeveloped reefs in unprotected areas north of Cozumel (Fig. 4), which could offer an alternative for harvesting ocean energy. Currently, tourism in these environments is centered on motorized water sports, the observation of surrounding pelagic life, and expert drift-diving due to strong currents ($U = 0.34$–0.7 m/s). Within this context, Table 2 summarizes the development of hotels, lodges, and a sheltered port in close association with the conditions described above.

Transition areas between environments with high and high-intermediate energy density levels (i.e., $E_D > 60$ J/m^3 and current speeds $U > 0.34$ m/s) occur in rocky and sandy profiles described by Muckelbauer (1990) with the presence of Anthothelidae, Rhodolites, Sargassum, or Xestospongia. The Chankanaab, Santa Rosa, Chun Chacaab, and Palancar profiles show this transition from high to intermediate energy density levels as bands over the profiles (Fig. 5), running parallel to the coastline (Fig. 4). Tourism and city infrastructure benefit from this kinetic marine energy transition in non-protected areas through the development of cruise- cargo- and passengers ship terminal piers, as well as the transit of ferries (Fig. 1). However, the transition in protected areas is related to tourism activities and theme parks including drift-, deep-, and wall-diving for intermediate to expert divers, snorkeling spots, swimming, observation of pelagic and coral life, as well as marine photography.

Energy-biotopes with $E_D > 60$ J/m^3 (high and high-intermediate energy density) contain Anthothelidae soft corals projecting perpendicularly from vertical walls, slope breaks, canyons, and crevices such as in the shelf-edge reefs (e.g., Santa Rosa wall) (Humann, 1993). In contrast, Rhodolites cover terraces and reef current channels in the shape of small free-living nodules at 0.03–0.3 m height (e.g., Corallineae, Peyssonneliaceae), forming habitats on which a wide variety of species can attach themselves, including corals and other algae (e.g., *Halimeda* spp., *Caulerpa* spp., *Sargassum* spp., *Dictyota* spp.) (Humann, 1993; Littler and Littler, 2000; Montaggioni, 2011) (Fig. 5 and Table 2). Organisms characteristically related to high-intermediate energy density levels ($60 < E_D < 250$ J/m^3) and flow speeds of 0.34–0.7 m/s include the following seaweeds: a) Rhodophyta (red algae) families, such as Corallineae and Melobesiae, heavily calcified and attached to hard substrates, coral fragments, debris, and coarse sand, often in seabed grasses from shallow to 30 m depth; b) Melobesiae, which regulate bio-erosion of the substrate; and c) algae such as Chlorophyta (green algae) and Phaeophyta (brown algae) represented by *Dasycladus* spp. and *Dyctiopteris* spp., found in shallow habitats (i.e., <10 m depth), on hard substrates (i.e., shell and coral fragments), and on sandplains (Littler and Littler, 2000, 2011), such as those occurring on the 2nd terraces of Chankanaab, Chun Chacaab, and Santa Rosa (Fig. 5 and Table 2).

Hard coral families described in ASK (2017) and Muckelbauer (1990) were observed to be primarily related to areas with intermediate energy density ($20 < E_D < 250$) (Figs. 4 and 5). In this regard, aquatic sports such as scuba and free-diving, as well as snorkeling for novice to intermediate skilled tourists, represent the most popular activities on Cozumel Island (Gallrein and Smith, 2003). A wide variety of coral species occur in these areas including Mussidae (*Manicina areolate* Linnaeus, 1758), Poritidae (*Porites Pallas*, 1766; *Porites astreoides* Lamarck, 1816), Faviidae (*Pseudodiploria strigosa* Dana, 1846; *Favia fragum* Esper, 1795), Siderastreidae (*Siderastrea radians* Pallas, 1766), Agariciidae (*Agaricia agaricites* Linnaeus, 1758) (Table 2). Similarly, flow conditions belonging to low-intermediate levels of energy density ($20 < E_D < 60$ J/m^3 and $U = 0.35$–0.50 m/s) (Fig. 5) are associated with shallow waters with little water movement or moderately wave-exposed areas (Fig. 4). In this energy-biotope, soft corals (*Briareum asbestinum* Pallas, 1766) and green algae (e.g., *Avrainvillea* spp. *and Rhipocephalus* spp.) grow as large paths together with seagrass (e.g., *Thalassia testudinum* K. D. Koenig, 1805) or on sandy plains between reefs (Humann, 1993; Littler and Littler, 2000) (Table 2).

The major component of sessile benthic fauna at low energy conditions ($E_D < 20$ J/m^3 and up to 0.35 m/s) are branched coral colonies of Gorgoniidae (Pseudopterogorgia, *Gorgonia ventalina* Linnaeus, 1758; *Pterogorgia anceps* Pallas, 1766), and Hydrozoos at heights between 0.3 and 2.0 m on isolated patch reefs over shallow slopes and terraces (i.e., <5 m) (Fig. 5 and Table 2). Underwater marine activities in low energy density biotopes are limited due to shallow water and proximity to the shoreline. Nevertheless, calm and safe waters are mostly used by resorts and eco-tourism parks.

Table 2 Summarizes Cozumel's marine energy biotopes, including energy density and the relationship with benthic distribution (Figs. 4 and 5). The table also describes the association with tourist activities and infrastructure.

4. Discussion and concluding remarks

Marine-based tourism in Cozumel Island has experienced large-scale growth since the 1960s due to significant economic benefits provided by local reef ecosystems. The development of cruise ship tourism for Cozumel Island represents 78–85% of tourist arrivals (Table 1), which, together with the local workforce supported by increasing mainland development (Palafox-Muñoz and Segrado-Pavón, 2008), is related to economic growth and, consequently, to an increase in electric energy consumption (Fig. 3). Rapid population growth and the combining of the national and international tourism market explains maximum annual population growth rates of 22.5%, an electricity demand of 2.7 GWh/capita, a 3.76 times increase in tourist arrivals over the last two decades (1997–2017) (currently 4.8 million), and annual revenue of up to US$ 762.6 million, reflecting a 4.41% annual average of the national income (Table 1).

Cluster analyses and linear trend models (eqs. (1) and (2)) show a direct correlation ($r^2 > 0.976$) and similarity (>90%) between tourist arrivals and both total revenue and electric energy consumption, leading to US$ 161.74 and 64.62 Wh per tourist, respectively. However, electric energy demand is in contrast with the reported 2749 kWh/capita (SENER-World Bank-ESMAP, 2015), labelling Cozumel with an

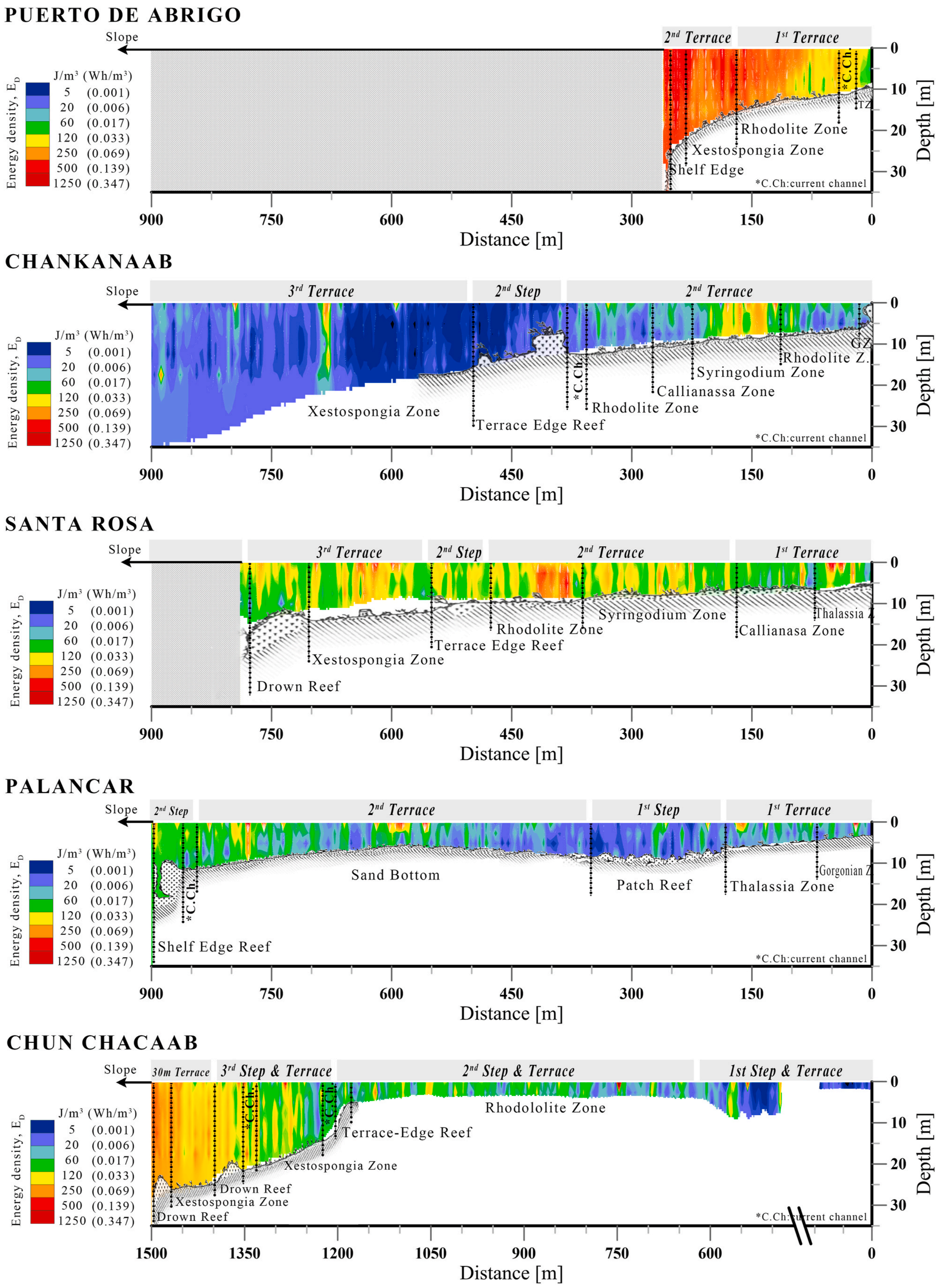

Fig. 5. Energy density profiles based on velocity measurements overlaid with reef profile biotopes described in Muckelbauer (1990). Profiles shown are perpendicular to the coastline, which is located at distance d = 0 m.

Table 2

Description of marine energy-biotopes as a function of energy flow conditions for selected profiles of Cozumel Island, based on velocity field measurements, energy estimates, and data obtained from ASK (2017), Barranco et al. (2016), Gallrein and Smith (2003), Martínez (2008), and Muckelbauer (1990).

ENERGY	Tourism activities and Infrastructure	Marine biotope description		
HIGH ENERGY/FLOW CONDITIONS **Energy density $E_D > 250$ J/m^3** (current speed $U > 0.70$ m/s)	Main tourist activities: • Swimming (limited to $<$ 30 m from the shoreline). • Drift-, deep-, and wall- diving (skill level: expert). • Motorized water sports. • Sport- and spearfishing. • Observation of pelagic life. Main infrastructure: • Development of hotels and lodges Sheltered port (Puerto de abrigo). • Influence of northern urban development. Non-protected area	FLORA	Seagrass: • Thalassia testudinum, Seaweeds: • Chlorophyta: Caulerpa spp., Halimeda spp. • Rhodophyta: Rhodolites. • Phaeophyta: Sargassum spp., Dictyota spp.	• Large Xestospongia and Rhodolite zones. • Areas densely covered with algae, large basket, and encrusting finger-shaped sponges. • Shelf edge and edge terraces. • Hard-ground, coarse-grained sand. • Drowned reefs and large ridge-shaped reefs. • Typical profiles: e.g., Puerto de abrigo.
		SOFT CORAL	• Anthothelidae (I. Schrammi). • Plexauridae (Plexaura spp.).	
		HARD CORAL	• Astrocoeniidae (S. intersepta, M. decactis). • Meandrinidae (D. Stokesi). • Mussidae (M. areolata). • Poritidae (P. astreoides, P. porites). • Siderastreidae (S. radians)	
HIGH-INTERMEDIATE ENERGY/FLOW CONDITIONS **Energy density, $60 < E_D < 250$ J/m^3** (current speed $0.34 < U < 0.70$ m/s)	Main tourist activities: • Drift-, deep- and wall- diving (skill level: intermediate to expert) and snorkeling spots. • Swimming (Ironman triathlon host). • Observation of pelagic and coral life. Marine photography. Main infrastructure: • International terminal pier. • Cruise ship terminal piers for Playa Langosta and Puerta Maya. • Official and cargo piers (ferry connection to the mainland). • Transit area for ferries. • Urban development. • Development of hotels and lodges • Theme park "Chankanaab." Protected and non-protected area	FLORA	Seagrass: • Thalassia testudinum, Syringodium filiforme, Halodule spp. Seaweeds: • Chlorophyta: Dasycladus spp., Penicillus spp., Udotea spp., Caulerpa spp., Halimeda spp., filamentous green algae. • Rhodophyta: Corallineae, Melobesieae, Laurencia spp. • Phaeophyta: Dictyopteris ssp., Dictyota spp. Sargassum spp.	• Very dense seagrass beds with current eroded- channels, oscillation ripple marks, coral debris, and coarse sand. • Large Xestospongia and Callianassa areas. • Multiple terraces of 10 m depth, crevices, and caves. • Typical profiles: e.g., Santa Rosa, Chun Chacaab, Chankanaab.
		SOFT CORAL	• Anthothelidae (I. Schrammi)	
		HARD CORAL	• Agariciidae (H. cucullata, A. agaricites). • Faviidae (Cladocora spp., M. cavernosa, D. strigosa). • Meandrinidae (E. fastigiata, D. stokesi). • Mussidae (M. areolata). • Poritidae (P. porites). • Siderastreidae (S. radians).	
LOW-INTERMEDIATE ENERGY/FLOW CONDITIONS **Energy density, $20 < E_D < 60$ J/m^3** (current speed $0.20 < U < 0.34$ m/s)	Main tourist activities: • Aquatic sports (e.g., swimming, snorkeling, paddleboard, windsurf). • Scuba and free- diving, night, and drift diving (skill level: novice to intermediate). • Observation of pelagic and coral life. Marine photography. Main infrastructure: • Resorts. Protected areas	FLORA	Seagrass: • Thalassia testudinum. Seaweeds: • Chlorophyta: Penicillus spp., Udotea spp., Caulerpa spp., Halimeda spp. • Rhodophyta: Rhodolites. • Phaeophyta: Padina spp., Dictyota spp.	• Seagrass beds (Thalassia), Xestospongia, and Rhodolite zones. • Sandy bottoms, shallow terraces ($<$ 10 m), patch reefs and current channels, coarse sand, coral debris. • Typical profiles: e.g., Palancar, Chankanaab
		SOFT CORAL	• Briareidae (B. asbestinum). • Plexauridae (Plexaurella spp., Eunicea spp.).	
		HARD CORAL	• Agariciidae (A. agaricites). • Faviidae (D. strigosa, F. fragum). • Mussidae (M. areolata). • Poritidae (P. porites, P. astreoides) • Siderastreidae (S. radians).	
LOW ENERGY/FLOW CONDITIONS **Energy density, $E_D < 20$ J/m^3** (current speed $U < 0.20$ m/s)	Main tourist activities: • Aquatic sports (e.g., swimming, snorkeling, paddleboard). • Diving (skill level: novice to intermediate). • Observation of pelagic and coral life. Marine photography. Main infrastructure: • Eco tourism "Punta Sur." • Lighthouse, Mayan vestiges. Protected areas	FLORA	• Encrusting and articulate red algae	• Xestospongia areas and sand bottoms. • Located closer to the shoreline and shallow terraces (i.e., $<$ 5 m). • Isolated patch reefs. • Typical profiles: e.g., Palancar, Chankanaab
		SOFT CORAL	• Gorgoniidae (Pseudopterogorgia, G. ventalina, P. anceps) • Plexauridae (Plexaurella spp., Eunicea spp., Pseudoplexaura).	
		HARD CORAL	• Agariciidae (A. agaricites). • Faviidae (M. annularis, P. strigosa). • Hydrozoans (M. alcicornis).	

apparent local consumption per capita that exceeds that of cities such as Rio de Janeiro, Bangkok, and Colombo. Nonetheless, in this study, cruise ship tourism is recognized as the leading player in electric energy consumption on the island with a floating population of 4.10 million, in comparison to the 0.08 million local population. In addition, the number of hotel rooms remained near constant (i.e., 4100 rooms) over the last few years (2010–2015) (Table 1). Therefore, indicators of the increasing electric energy demand of the floating population should include the direct and indirect end-users of energy from cruise ship tourism.

The use of the marine "energy-biotopes" considers the energy as an attribute allowing the incorporation and association with other features such as the distribution of the benthic environment as well as the development of tourist activities and human infrastructure (Table 2). For example, the classification of energy-biotopes allows for the differentiation of biotopes that are feasible for marine energy harvesting from those that support various tourism activities/infrastructure for Cozumel (Table 1) as follows:

- Biotopes with high-energy densities ($E_D > 250$ J/m^3) in northwestern Cozumel (20.517–20.573° N) are associated with rocky ledges and terraces, as well as coral reef structures of low development (Figs. 4 and 5). This energy-biotope may provide the most suitable location for the harvesting of marine renewables (Alcérreca-Huerta et al., 2019b). Tourism activities are not highly developed in this area and no marine reserves have been declared to protect the reefs due to the following: i) its proximity to population settlements, ii) expert skills required for conducting underwater marine activities, iii) flat coral reef colonies, iv) specific dominant algae environments, iv) edge terraces and a narrow marine platform (<500 m), and iv) high flow speeds (>0.8 m/s). For instance, San Juan and Barracuda reefs represent the northernmost formations on the west-insular shelf of Cozumel, featured by low reef structure heights (Fig. 4) and environments dominated by deep and rocky ledges.
- Biotopes of intermediate to low energy densities ($E_D < 250$ J/m^3) are often mixed within reef profiles and mostly occur within the protected areas of Cozumel (DOF, 2016, 2012, 1996), due to the following: i) valuable landscapes, ii) well to highly developed coral reef cover and structures (Fig. 4), iii) lower specific dominance of algae, iv) few human infrastructure developments, but v) higher pressure from diving, deep-sea fishing, snorkeling, and large-scale sporting events (e.g., Ironman Triathlon). In this energy-biotope, reef structure and cover, as well as the value that comes from avoiding reef degradation (Pendleton, 1995), represent the foundation for tourism and the primary economic income source for Cozumel.

The use of the higher energy density biotope as a renewable marine energy resource could eventually provide benefits to tourism development. However, the effects on pelagic organisms that are not important to tourists but are ecologically significant, such as sharks, eagle rays, marlin, lobsters, turtles (ASK (2017)), and coralline algae should be assessed. The latter is relevant in the context of global change, ocean acidification, blue carbon cycle, and calcium carbonate production in continental and insular shelves (Amado-Filho et al., 2012; Foster, 2001; McCoy and Kamenos, 2015).

Ocean energy has been recognized as an alternative or potential energy resource to fulfil policies and strategies focused on renewable energy-based systems. It is well known that energy levels are important to environmental functioning, and that marine renewables have the potential to induce change (Copping et al., 2014; Dannheim et al., 2020). Although studies have looked at this issue, the majority focus on wave and tidal energy in temperate environments with threats from construction, functioning, and decommissioning of energy converters (Fortune and Paterson, 2020; Uihlein and Magagna, 2016), as well as mechanical, electromagnetic, or chemical effects on pelagic organisms (e.g., mammals, pelagic fish, seabirds, and sea turtles) (Copping et al., 2020; Henkel et al., 2014; Kregting et al., 2016). Information or analyses are rarely related to marine energy from the ocean currents generated by the global ocean circulation, which differ from tidal energy due to their almost constant and unidirectional flow. The analysis of the ocean currents generally focus on hydrodynamic effects (e.g., flow redirection and water level drop) (Haas et al., 2017; Yang et al., 2014), but they are not related to the socioecological context of tropical reef systems with high ecosystem value, such as Cozumel Island. We suggest that implications and changes of marine energy-biotopes should not only focus on anthropogenic needs and resource use in the light of human-energy consumption and, within this context, the investigation of kinetic marine energy density in the biotopes herein presented aims to establish the energetic environment of the reef ecosystems in Cozumel. However, further quantitative measurements in the form of biotope monitoring are essential for further assessments of marine energy, cover, abundance, and distribution. The energy density map herein presented only considered the spatial variation of the current over the insular shelf, thus research is still required to account for temporal variations of the current, its interaction with waves and the coral species distribution.

Currently, the development of sustainable tourism schemes and policies for Cozumel Island includes renewable energy within a feasible energy portfolio (Anaya-Ortiz and Palafox-Muñoz, 2007; SENER-World Bank-ESMAP, 2015; UNESCO, 2017). Environmental implications from harvesting ocean energy need comprehensive analyses as investment is likely to grow (Kerr, 2007; Pelc and Fujita, 2002). In Cozumel Island, energy from ocean currents could meet approximately 10% of electric energy demands (Alcérreca-Huerta et al., 2019b) through technological developments appropriate to the marine energy conditions in the area (Encarnacion et al., 2019; Encarnacion and Johnstone, 2018). However, about 150 turbines of approximately 5 m diameter may be required and placed in high-energy areas with energy density >250 J/m^3 (Alcérreca-Huerta et al., 2019b), and without an environmental and conservation status (Fig. 4). Thus, the continuous evaluation of energy-biotopes in Cozumel Island is required to avoid the sustainability paradox within the tourism sector that describes the reliance on the use of natural resources that are simultaneously needed to ensure an attractive and functional natural environment for its development (Anaya-Ortiz and Palafox-Muñoz, 2007; Segrado et al., 2008; Solis-Weiss et al., 2007). The impact of tourism on the coastal environment of Cozumel has been referred to as a type of theoretical "self-destructive tourism" (Nim, 2006) as defined in Davenport and Davenport (2006) and Holder (1988). Therefore, energy policies as well as environmental and tourism management strategies should engage in the development of a sustainable framework that does not overburden the current resource capacity and notion of environmental space (Amin, 2008; Randolph and Masters, 2018; Spangenberg, 2002). Strategies, regulations, analyses, and interdisciplinary approaches are required to overcome technological, efficiency related, environmental, economic, and social constraints related to the development of sustainable tourism (Borthwick, 2016; Jones and Hillier, 2016; Wilkinson, 1999, 2012). Further studies are needed to assess energy and environmental issues accompanying the rapid economic, tourism, and population growth in Cozumel.

The classification of energy-biotopes herein presented provides a basis for the analysis of marine energy, the use of a mixed renewable energy matrix (Mendoza-Vizcaino et al, 2016, 2017), as well as the replacement and/or widening of the capacity of underwater electricity lines between Cozumel Island and the mainland (Solis-Weiss et al., 2007). The description of marine energy-biotopes may also provide an integral vision to enhance tourism development by encouraging the conservation of local biodiversity, reduce risk-related uncertainties while considering long-term human impacts, and potentially, decrease negative impacts on a valuable marine environment (Hammar et al., 2017; Inger et al., 2009).

- Cozumel electric tourism demands, reef environment, and marine energy are analyzed.
- Energy is examined as a biotope attribute rather than a resource for exploitation.

- Marine energy biotopes could describe links among benthic environments and tourism.
- High-energy biotopes could contribute to ocean renewable kinetic energy harvesting.
- Low-energy and intermediate-energy biotopes relate to tourism-attractive reef structures.

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.

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