Resource assessment of the marine current developed in the Cozumel Channel

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Abstract*—Renewable energy based systems are expected to contribute on the reduction of greenhouse gases and carbon emission, while satisfying global energy demands. In Mexico, the Cozumel Channel located in the Caribbean Sea has been identified as a potential energy source in the region. Preliminary studies have shown that the ocean current is characterized by almost uniform and unidirectional flow velocities of up to 2.0 m/s within its mid-section with water depths > 500 m. Nevertheless, a detailed resource assessment in shallow waters of the Cozumel Channel is required to address sites potentially suitable for the installation of marine energy converters. Field measurements were taken during September 23rd-29th, 2018 to describe the spatial variation of the marine current velocities at various points along the east-side of the Cozumel Channel, at water depths less than 50 m. Flow velocities higher than 1.0 m/s were identified on the northern east of the Cozumel Channel, at a distance >600 m from the shoreline and over the continental shelf with water depths <50 m. Both energy and power intensity exceedance curves were developed from depth averaged velocities from ADCP measurements. Potential sites were identified where an array of marine energy converters could be installed preventing the devastation of the rich ecosphere renown in the region.

Paper ID: 1362. Conference track RC 49/1362/DV/87.

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***Keywords*—Cozumel Channel, marine renewable energy, marine current.**

I. INTRODUCTION

TIDAL and ocean current energy resources represent a theoretical potential of 25880 TWh [1] and 800 TWh per annum, respectively [2], based on annual sea surface elevations and water depths as well as on surface velocities of ocean currents. Continuous technological advances within the tidal energy industry have contributed to the progress of the sector. Up to date, the development of tidal energy conversion is normally focused on high latitudes and locations where tidal streams are higher than 2.5 m/s, thus limiting the implementation of these technologies to specific regions and decreasing opportunities for large-scale commercialisation.

The kinetic energy from ocean currents could represent a feasible and potential alternative to harvest energy. Contrary to tidal energy streams, ocean currents are characterised by developing almost uniform and continuous flows, especially at locations where the geomorphology of the site exacerbates the flow velocities (e.g. straits, channels). Nevertheless, studies quantifying the energy potential of ocean currents are currently limited. It is likely that tidal stream technologies can also be implemented in locations these currents are available but should also account for adaption to high biodiverse and productive environments such as in the tropics.

Renewable energy alternatives such as photovoltaic systems (PV) and offshore wind turbines have been analysed for Cozumel Island [3], but not accounting for the potential ocean energy sources in the area. In this regard, the Cozumel Channel located in the Mexican Caribbean Sea (Fig. 1), has been identified as a potential energy source in the region with almost uniform and unidirectional flow velocities [4]. Currently, few methodologies and attempts have been developed for the use of marine renewable energy sources located in Mexico.

Therefore, the present paper aims to explore the potential of the ocean current resource developed at the Cozumel Channel in the Mexican Caribbean through a detailed spatial resource assessment of sites potentially suitable for the installation of marine energy converters in shallow waters. The measurements undertaken in this study have been focused in areas no deeper than 50 m as these regions will be suitable for marine array deployments in early stages of development, reducing excessive installation and maintenance costs associated with distances and water depths. This will provide awareness on marine current power that could be harnessed in the region. This study is expected to contribute on the development of emerging marine energy technologies under slower-stream conditions (when compared to tidal induced currents), generally found in the tropics.

II. Study Area

The Cozumel Channel is located in the Mexican Caribbean, limited by the Cozumel Island and the Peninsula of Yucatan (Fig. 1). It is approximately 50 km long and 18 km wide, with varying depths of up to 500 m [5]. Due to its geographical position, the passage of currents within the Cozumel Channel occurs from south to north [5,6].

The ocean currents within the Channel are developed as the flow stream deviation of the Yucatan Current by Cozumel Island. The Yucatan Current transports warm water from the Caribbean Sea and moves northwards to the Gulf of Mexico as one of the fastest currents in the Atlantic Ocean. The flow speeds are nearly uniform and unidirectional throughout the Cozumel Channel [5], reaching up to 2 m/s [7,8]. The understanding of the circulation and description of the ocean current within

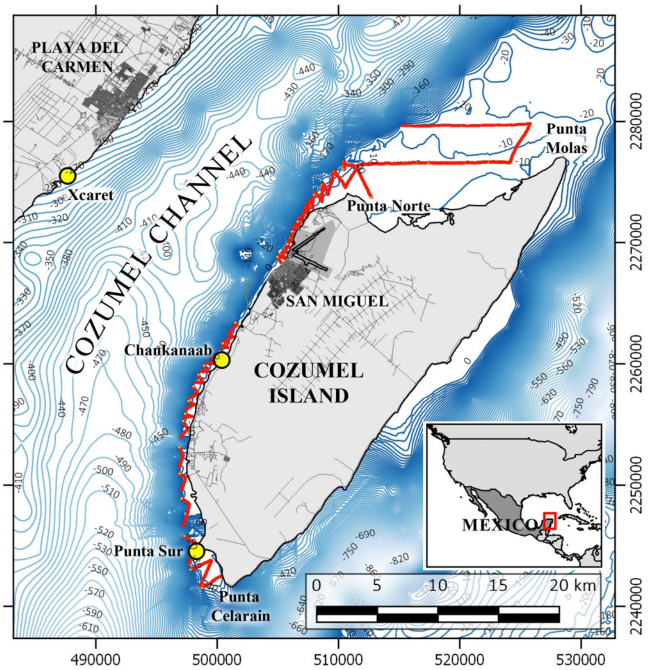

Fig. 1. Location of (a) Cozumel Channel, (b) main cities in the area (grey-shaded), (c) ADCP transects conducted during field survey (red lines) and (d) pressure sensors deployment (yellow marks). Bathymetry of the study area is also shown.

the Cozumel Channel has been the focus of most existing studies in the area, although the methodologies normally used do not consider the coastal areas or depths between the 0-50 m, where the energy extraction by ocean currents could be implemented as a first approach.

In the study area, astronomic tides do not represent the main forcing as the ocean current flow within the Cozumel Channel. For the Caribbean Sea, microtidal conditions are mostly found with reported values of the tidal range around 0.2 m [9]. According to [10] and based on in-situ long term records, a tidal range of ~0.18 m could be found at Cozumel Island. Thus, tidal range differs substantially from typical values commonly found in tidal streams.

The shelf along Cozumel Island and mainland Mexico is ~250-500 m width, reaching water depths of 35-50 m. However, in the northern area, a sandy insular shelf extends several kilometers seaward (Fig. 1). In the east shallow waters of the Cozumel Channel, bordering the Cozumel Island, a complex ecosystem of coral reefs covers a total area of about 17 km^2 featured by discontinuous formations as well as edge and platform reefs [11].

The reef systems constitute the major attraction for Cozumel since the 1950s. Moreover, Cozumel Island is the largest of the Mexican islands in the Caribbean Sea, the most populated as well as the most important cruise destination in the country. Thus, due to its ecological importance, fragility and intense tourism development, around the Cozumel Island and the Cozumel Channel, marine natural protected areas are found. Therefore, marine energies could potentially provide the energy demands of local communities and of the tourism that has exponentially increased since the 1970s.

III. Methods

Field measurements were conducted during a field survey (September 21st to 29th, 2018) in order to explore the potential of the ocean current over the east shallow waters of the Cozumel Channel. An Acoustic Doppler Current Profiler mounted shipboard (RiverPro ADCP) with a fully integrated GPS was used in order to describe the spatial variation of the marine current velocities. The ADCP transects were performed at (Fig. 1):

1) The northern area between Punta Norte and Punta Molas, where linear transects were conducted in the extended shore platform.
2) The insular shelf between Chankanaab and Punta Norte, which belongs to the narrower section of the Channel.
3) The southern portion of Cozumel Island, from Punta Celarain to Chankanab. This region is the inlet to the Cozumel Channel, with Punta Celarain as the divergent point for the passage of currents towards the channel.

The spacing between transects was of ca. 2 km from Punta Sur to Chankanaab, and about 0.5-1.0 km near

Punta Norte, where increasing flow rates were identified in combination with sandy seabed and a low presence of coral reefs.

The ADCP measurements on the shore platform covered most of the west coast of the Cozumel Island, with the exception of the area where ferry crossings are developed (i.e. cargo and passengers) mostly around San Miguel city and in which navigation is prohibited within a buffer zone around the boarding area. The ADCP transects were limited over the insular shelf at water depths of ~ 35 m, just before the development of the steep insular slope towards the middle section of the Cozumel Channel.

Bathymetric data was also recorded during the campaign with ADCP and probe data from a GPS-Humminbird 899 CXI HD SI. These measurements were conducted as existing and public bathymetries through the Nautical Charts of the Navy (Charts 924.000 and 922.500) do not provide enough detail on the insular shelf of the study area. Transects correspond to those also obtained with the ADCP, with the bathymetric data gathered at a sampling frequency of 0.1 Hz for further analysis by means of SonarTRX Pro X64 (extraction of XYZ data) and GIS tools.

CTD profiles were also conducted to identify the variations of temperature and salinity in the study area. These parameters were also used to determine the barotropic or baroclinic condition over the insular shelf. The composition of the vertical profiles throughout the water column was also evaluated to establish the presence of flow stratification which in turn will imply load variations on a marine energy converter.

In addition, temporal variations of water level were measured considering the deployment of HOBO sensors (June 22nd – September 29th) at Punta Sur (20.29853°N, 87.01632 °W), Chankanaab (20.44111°N, 86.99639°W) and Xcaret Parks (20.57826°N, 87.11834°W) (Fig. 1). It must be noted that these locations are along Cozumel Island and in mainland Mexico, which permitted the evaluation of water elevation at both sides of the Channel as a proxy to tidal ranges within the study area.

IV. Results

Temperature and salinity profiles from all field measurements along the east coastal area of Cozumel Island are shown in Fig. 2. The maximum recorded values of salinity and temperature were 39.7 PSU (practical salinity units), and 31.71 °C, respectively. The minima were of 33.6 PSU and 28.45 °C. Also, average values for all the study area were of 37.0 PSU and 29.3 °C (Fig. 2), thus leading to an average water density of 1023.5 kg/m^3. These values featured the key parameters from water properties.

Almost all vertical CTD profiles exhibit a highly homogeneous behaviour for salinity along the water column. In general, temperature profiles describe a slight uniform decrease as function of the depth, but which does not exceed ~1.0°C. Homogenous performance of the profiles is clearly defined, thus representing barotropic conditions in the Channel during the field survey period but which could also be present as consequence of the mixing induced by the ocean current. Nevertheless, further measurements and analysis of HOBO sensors should be conducted to observe their variability throughout the year.

The average density was considered for the calculation of the energy and power per unit area in combination with ADCP measurements, as it was also homogeneous along the east coast of Cozumel Island.

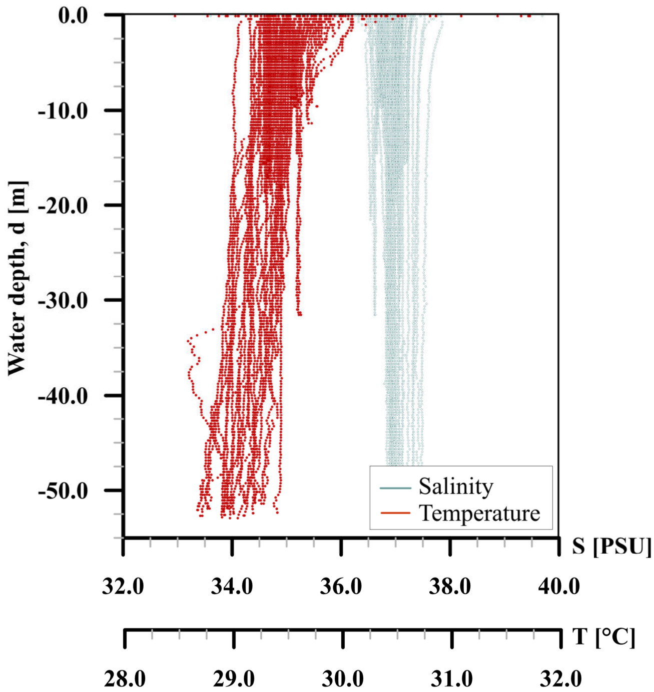

Fig. 2. Salinity (S) and temperature (T) profiles from CTD field measurements along the east coastal area of Cozumel Island.

The variation of the sea water level is exemplarily shown in Fig. 3, taken from the HOBO pressure measurements at Chankanaab, covering the same time period of CTD profiling and ADCP measurements (September 23rd – September 29th, 2018).

Semidiurnal micro tidal behaviour is clearly noticed in Fig. 3. The average tidal range within the 7-days period was of 0.23 m and a standard deviation $\sigma = \pm\ 0.037$ m, which is in the order of magnitude of previous studies [9,10]. A maximum tidal range of 0.29 m was observed, whereas minimum values of 0.16 m were found. These variations are likely to be expected as a consequence of local meteorological conditions (i.e. winds) that could slightly modify the water elevation at both sides of the Cozumel Channel.

This result shows the microtidal regime at Cozumel Channel, providing additional evidence that the current flow is mainly driven by the ocean current with minimum effects from tides.

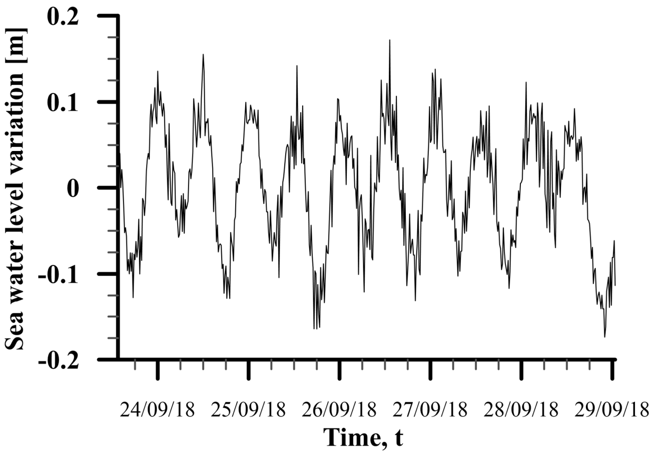

Fig. 3. Sea water variation from HOBO measurements at Chankanaab (20.44111°N, 86.99639 °W) during September 23rd–September 29th, 2018.

The echosounding measurements provided information related to the formation of terraces where reef formations are discontinuously developed. Over the narrow insular shelf of the Cozumel Channel (< 500 m width), a terrace of about 20 m depth is formed prior to the end of the shelf. Formations of mounds were also identified after which the insular slope develops (Fig. 4). In this regard, the insular shelf presents a very steep slope, dropping from 40-50 m to 150 m depth in a very short distance (~ 600 m); i.e. a non –homogeneous slope of about 1:6. A wide terrace in the northern east area was also identified and which extends norward, however, this area is mainly comprised by shallow waters with average water depths between 10-15 m, almost developed over sandy bottoms.

Rose diagrams of currents were obtained using ADCP data. For instance, depth averaged velocities between latitudes 20.270°N and 20.585°N are shown in Fig. 5. Predominant flows directed N-NE were observed, with the largest magnitudes and values greater than 1.2 m/s towards the NE (40-50°) (east assumed as zero reference and increasing anticlockwise). Flow directions varied between 30°<θ <90° for velocity magnitudes greater than 0.6 m/s and mostly aligned to the main flow of the ocean current.

The higher velocities were mostly observed in the northern region of the Cozumel Channel, particularly close to Punta Norte, where the maximum velocity registered was of 2.7 m/s. The maximum velocities over the insular platform are mainly developed along a narrow strip of about 250 m before reaching its edge and between latitudes 20.50 and 20.57 °N (Fig. 4). Flow velocities decrease considerably in the area between Punta Norte and Punta Molas, where the Channel stretches. Flow velocities in that area were found around 0.2-0.3 m/s.

Histograms and exceedance curves were determined for four selected transects T1, T2, T3 and T4 (Table I) in the northern area and uniformly spaced, based on the results shown in Fig. 4 and Fig. 5.

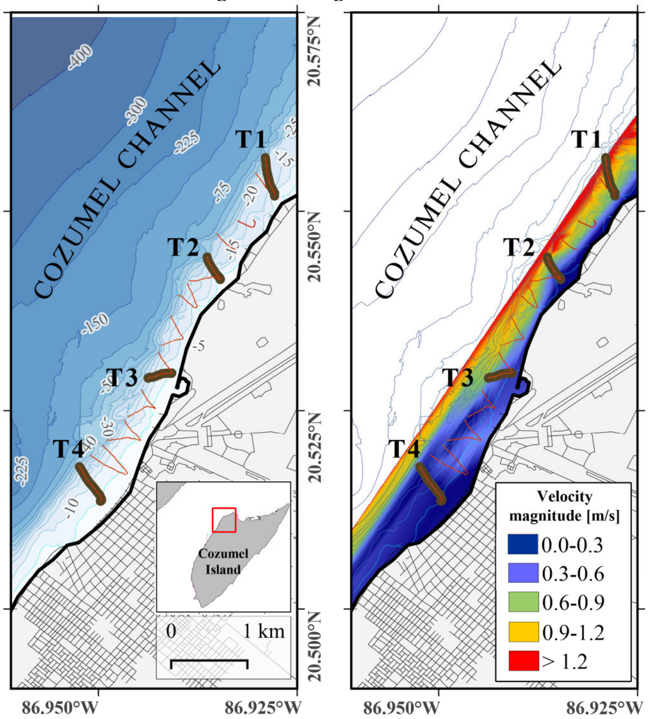

Fig. 4 Bathymetry (left panel) and depth-averaged velocity magnitudes for the northern zone close to Punta Norte (i.e. latitude 20.485 °N-20.575 °N).

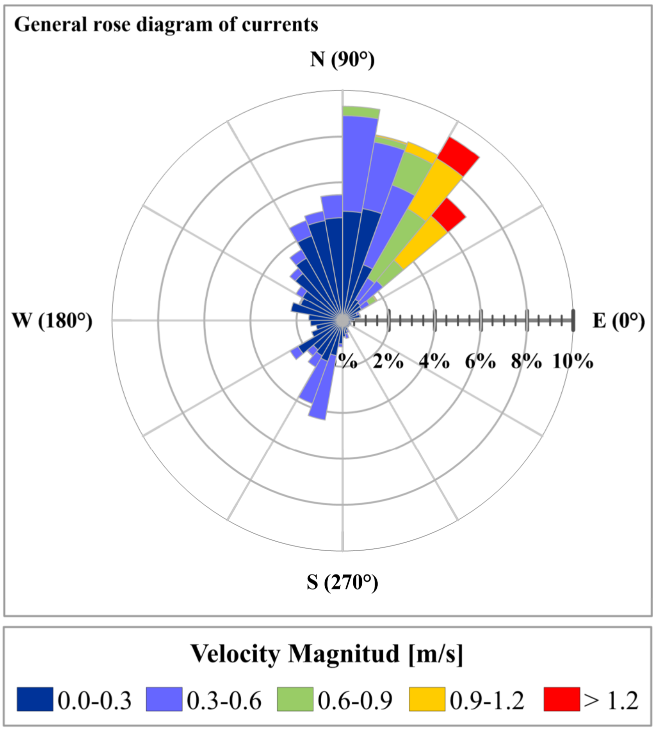

Fig. 5 Rose diagram of currents within the east coastal shallow waters of the Cozumel Channel.

The histograms contain information on the distribution of velocity magnitudes at each transect as well as the increase of the ocean current northward, whereas the exceedance curves consider the cumulative frequency of exceedance, thus determining the probability of velocities, energy and power estimates of the region.

TABLE I
DEFINITION OF TRANSECTS T1-T4 IN THE NORTHERN WEST COAST OF THE COZUMEL CHANNEL.

Transect		Coordinates		[a]Length
		Latitude (°)	Longitude (°)	(m)
T1	*Start*	20.5524	-86.9279	489
	End	20.5567	-86.9290	
T2	*Start*	20.5414	-86.9347	357
	End	20.5443	-86.9363	
T3	*Start*	20.5291	-86.9436	290
	End	20.5297	-86.9409	
T4	*Start*	20.5138	-86.9496	540
	End	20.5179	-86.9524	
		Average		419

[a]The transect length varied due to the width of the insular platform and accounting for water depths < 50 m.

Histograms for the velocity magnitudes recorded at the selected transects T1-T4 are shown in Fig. 6. Mean values of V_{Mag} were obtained given by 0.98, 0.80, 0.51, and 0.29 m/s with standard deviations of 0.30, 0.29, 0.26 and 0.13 m/s for transects T1, T2, T3 and T4, respectively. In average, this represents a velocity among transects of 0.65 m/s and an average standard deviation of 0.25 m/s.

The increasing velocity magnitude northwards is clearly noticed in Fig. 6 and on the average velocities per transect. For T4 velocity magnitudes are found between 0-0.6 m/s. A bimodal distribution for T3 is developed with peak velocities ~0.3-0.4 m/s and ~0.7-0.8 m/s. This could be related to the effects of the main current flow from the centre of the Cozumel Channel, which could get closer to this location and adds to the ongoing flow which is further developed in T1 and T2 with an increasing tendency for velocity magnitudes. These velocities were increased in general by 0.2 m/s between transects; i.e., an increasing rate of ~0.26 m/s per kilometre reaching velocity magnitudes > 1.0 m/s at T1 with an accumulated frequency of ~40 %. Transect T1 provides a broader insular shelf just before the stretching end of the Cozumel Channel and thus, more influenced by the main flow passing through, in comparison with T2, T3 and T4. Despite the fact that larger velocities are observed for T1, the variation of velocities between ~0.4-1.8 m/s could represent an important challenge for turbine design. Also, according to Fig. 4b, the lower velocities are observed closer to the coastline, and the higher velocities occur nearly the limit of the insular shelf as previously mentioned.

Regarding the flow direction, the mean direction was of 50.0, 51.4, 55.4 and 64.7 ° with a standard deviation of 14.5, 13.6, 26.5 and 23.8 ° for transects T1, T2, T3 and T4, respectively. The average direction among these transects is thus of 55.4 ° and a standard deviation 19.6 °.

The change on direction from the NE to the NNE, from T4 to T1, is mainly caused by the northward variation of the coastline. Larger fluctuations of flow direction are observed at T3 and T4, whereas it is reduced for T1 and T2 (more influenced by the main flow of the ocean current as similar to their velocity magnitudes).

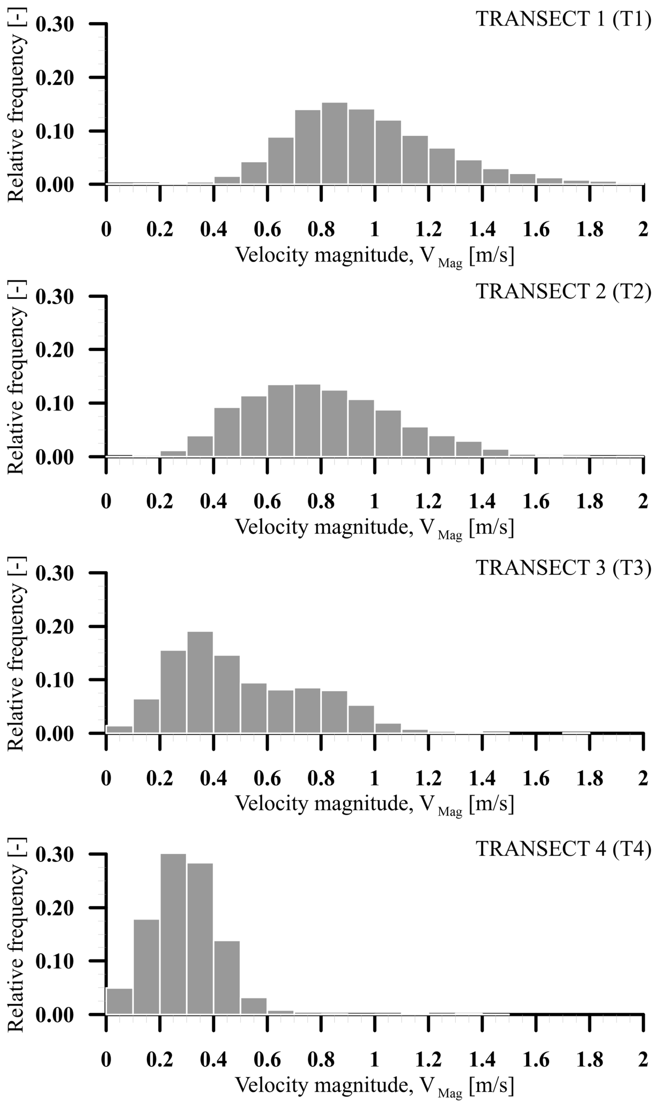

Fig. 6. Histograms for velocity magnitudes recorded for the selected transects T1, T2, T3, T4.

The exceedance curves for both energy density (E_D) and power per unit area (P/A) were calculated considering (1) and (2), expressed in Wh/m³ and W/m², respectively.

$$E_D = 0.5\rho V_{Mag}^2/3600 \quad (1)$$

$$P/A = 0.5\rho V_{Mag}^3 \quad (2)$$

The velocity V_{Mag}, was taken from the ADCP measurements at each cell along the water column and for each transect. The density ρ considered a value of ρ=1024 kg/m³, obtained as the average from CTD measurements.

Power and energy per unit area (Fig. 7) reached up to 0.50 Wh/m³ and 3.35 kW/m², respectively, thus representing the maximum potential of the ocean current within the study area and for the period measured. These values have a probability of exceedance of ~1.0% according to that shown in Fig. 7.

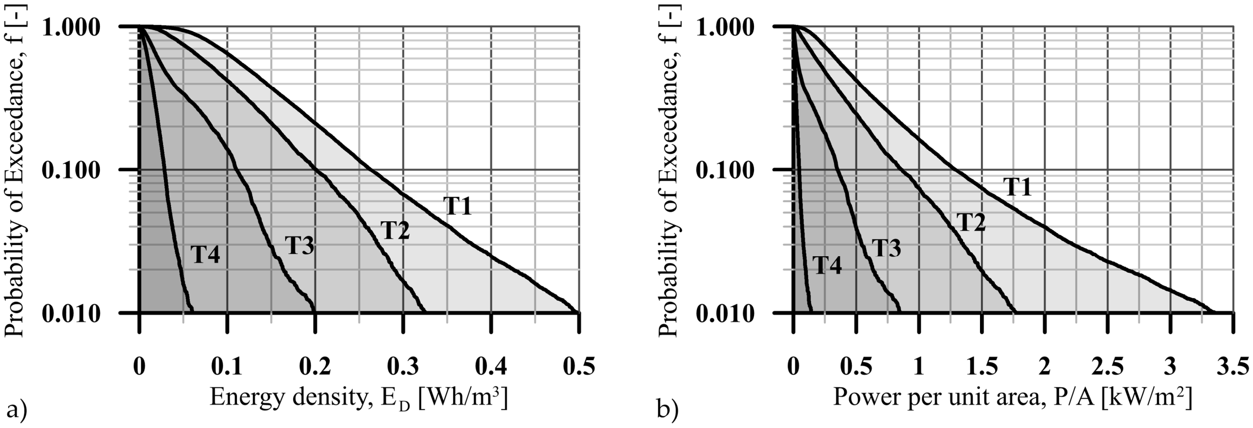

Fig. 7. Exceedance curves for (a) energy density and (b) power per unit area for selected transects T1, T2, T3 and T4 in the northern area of the east shallow waters of the Cozumel Channel.

In spite of the previously described maximum values, for an exceedance probability of energy with f = 10%, the energy density was of $E_{D,T1} \approx 0.263$ Wh/m³, $E_{D,T2} \approx 0.201$ Wh/m³, $E_{D,T3} \approx 0.110$ Wh/m³ and $E_{D,T4} \approx 0.029$ Wh/m³, whereas the power per unit area was of $P/A_{T1} \approx 1.29$ kW/m², $P/A_{T2} \approx 0.86$ kW/ m², $P/A_{T3} \approx 0.35$ kW/ m² and $P/A_{T4} \approx 0.05$ kW/ m².

Moreover, for an exceedance probability f = 50%, the energy density resulted in $E_{D,T1} \approx 0.125$ Wh/m³, $E_{D,T2} \approx 0.086$ Wh/m³, $E_{D,T3} \approx 0.028$ Wh/m³ and $E_{D,T4} \approx 0.012$ Wh/m³. For the same probability $P/A_{T1} \approx 0.42$ kW/m², $P/A_{T2} \approx 0.24$ kW/m², $P/A_{T3} \approx 0.05$ kW/m² and $P/A_{T4} \approx 0.01$ kW/m². When observing these last results as well as the exceedance curves (Fig. 4), transect T1 seems to be the most feasible location for the placement of energy converters, due to the large probability for obtaining higher values of energy and intensity of the current as well as for the intensification of the current nearby.

It is noteworthy to mention that the exceedance curves developed belong to an analysis of all ADCP cells within each transect. Thus, the results of both energy and power per unit area and the exceedance curves could change according to the section of the transect analysed; i.e. when focusing in a certain portion of the transect. Moreover, it would be required a temporal assessment of the energy and power but focused on most prone locations for harvesting energy from the ocean current.

V. Discussion

The resource quantisation of a site represents a fundamental element for assessing the magnitude of loads and hydrokinetic conditions, which aims to enhance technological development for existing and upcoming energy conversion systems [12,13].

Maximum velocity magnitudes were found near the cliff and about 150 m landward, so that, the spatial measurement has allowed detecting and refining the identification of areas in the coastal portion with a real potential for exploitation. The most important site is located close to the northern area of the Cozumel Channel at Punta Norte where speeds up to 1.2 m/s (0.9 kW/m²) are reached over the insular shelf (< 50 m water depth) along the east side of the Cozumel Channel.

A clear increasing rate of ~0.26 m/s per kilometre reaching velocity magnitudes > 1.0 m/s was found within the transects analysed, which could be related to the ocean current approaching over the insular platform of Cozumel Island.

Exceedance curves of energy and power per unit area as well as the most relevant features of the flow velocity magnitudes were also described for this site. Considering a probability of exceedance of 10%, about 1.29 kW/m² could be obtained. It should be accounted that higher speed could be achieved within the Cozumel Channel, however, water depths increase significantly up to 500 m due to the slopes of the insular shelf. Microtidal conditions and tidal range (~0.23 m) were found to be similar than those provided by [9,10] and so the measured velocities are mainly driven by the Yucatan ocean current within the Channel.

The evaluation of the Cozumel Channel current and results of in-situ assessment of marine energy resources show important limitations of the existing technological development to harvest slower-moving currents. However, recent efforts such as those presented by [14] have initiated novel advances, in order to capture energy from currents similar to those in the Cozumel Channel (i.e. < 2m/s). Given the flow intensities at the Channel, an estimated power capacity of a turbine will be in the order of 40-50 kW at 1.5 m/s if considered a power coefficient C_P=0.4, thrust coefficient C_T=0.7, a TSR=7.0 and a 10 m diameter rotor.

The energy and intensity values obtained in this study are lower compared to that reported for tidal streams as in sites such as the Chacao Channel, Chile and Puget Sound, USA; where the intensity of the power is approximately 2-4 kW/m² [15]. Also, the power capacity is notably lower if compared with tidal currents in high latitudes. However, the ocean current at the Cozumel Channel could provide a major advantage, a higher capacity factor due to the permanent and continuous flow if compared to tidal currents that, although predictable, run for a limited time and at alternating intervals according to the tidal cycle. This represents an expected considerable increase of potential in kWh that might also vary upon the optimisation of turbine arrays to be deployed [16].

The ocean current directionality was also described as almost unidirectional northwards (~40-50°) but with fluctuations of about ±19.6°. The flow directionality variation could lead to important power losses, structural loadings and capacity factors [17]. However, the current within the Cozumel Channel is not affected by flow reversing as given by ebb to flood or backwards under tidal currents.

Most of the current research is still focused on tackling problems related to excessive loading in the rotor and drivetrain components by implementing innovative solutions such as flexible materials and control strategies (e.g. [18,19]). Thus, challenges as those herein mentioned should be addressed before a feasible implementation of energy converters could be overtaken at the Cozumel Channel, for which an integrated development of both turbine designing and detailed resource assessment should be conducted.

The present resource assessment only considered the spatial variation of the current along the east coastal area of the Cozumel Channel as primary step to identify potential sites for harvesting the flow velocities over the insular shelf. Future research will be thus required to evaluate the ocean current potential in terms of temporal variability, mainly at the locations where the largest spatial potential was located (i.e. between latitudes 20.50 and 20.57 °N). Indication of the turbulence scales through detailed temporal studies will be required as a critical factor to inform the turbine architecture development when deployed at specific locations as it has been shown a significant effect on the loading fluctuations seen by the turbine; thus, compromising the device's structural integrity [20].

Effects such as the bimodal tendency of the currents need to be further explored, as to define the patterns that develop each of the dominant flow velocities. Additionally, physical characteristics of the ocean current at the study area were provided, but studies still lack from the ecological and environmental implications for extracting marine energy. The reduced presence of sensitive coral reefs and shallower waters make the development of an operational monitoring platform more feasible in the north area of Cozumel Island. Nevertheless, the sites also need to be further evaluated by addressing the interests and engagement of other interested stakeholders and potential environmental or legislative restrictions and limitations.

Different types of tidal stream energy converters have been conceptualised since the development of the first tidal stream device by Seaflow [21,22] but failed to succeed to Technologial Readiness Levels (TRL) greater than 3 or 4, with only ~12 % advanced to TRL 5-7. Therefore, preliminary assessment of the available resource will provide further desirable efficiencies and increasing the viability and capability of the designs/projects.

Therefore, an integral approach ranging from physical and biological processes as well as understanding the possible socio-economic impacts is required for the region since Cozumel has a large dependency on the ecosystem services (e.g. reefs, mangroves and nursery sites) that form a keystone on the economic activities.

VI. Conclusions

The depth-averaged velocity measurements from ADCP as well as both energy and power intensity exceedance curves were calculated in the study area. Potential sites were identified and where environmental conditions could also provide a feasible area for marine energy harvesting purposes. Histograms and velocity distribution map showed that most of the flow velocities fall between 0.8 and 1.0 m/s, particularly within a strip of ~5 km long and ~200 m width between San Miguel and before Punta Norte with an increasing rate of 0.2 m/s per kilometre. Variations of the flow directionality were also described to be of ± 19° in that area which are of similar magnitude to those found in tidal streams, and should be considered when engineering marine energy technologies. Also, power per unit area of 300-500 W/m^2 with a probability of exceedance of 50% was found.

Despite the lower power magnitude, important advantages of the ocean current in the Cozumel Channel are described by: i) a continuous and almost permanent flow conditions (independent from tidal cycles); ii) almost unidirectional flows with limited fluctuations; iii) no strong tidal influence; iv) bathymetric elements such as terraces followed by steep slopes and mounds. These conditions differ from those normally found in high latitudes, but stand for a wider approach of slower-moving currents and so, of the benefits to renewable energy based systems. Therefore, the resource assessment provides a basis for the development of renewables in the area and the engineering of marine converters.

Technological advances have been conducted on marine renewables, with free-tidal stream devices (e.g. HATTs) as one of the most developed within the sector and which can be further enhanced to harvest ocean currents such as that in the Cozumel Channel. This may open up the possibility for the implementation of marine renewable energies in the region, but also providing economically viable projects for further developed countries and tropical regions under similar conditions.

Assessment of both spatial and temporal variations is still required together with environmental characteristics in prime locations for marine energy harvesting. This will further encourage and strengthen the applicability of integral and multidisciplinary approach aiming to successfully implement marine energies in the region with benefits for tourism, economics and the preservation of natural environments.

ACKNOWLEDGEMENT

This work was supported by the Newton Fund Institutional Links and CONACYT-SENER-Fondo de Sustentabilidad Energética-Institutional Links under grants IL5 332324562 and 291380, respectively. Support and permits for field measurements issued by the National Commission of Natural Protected Areas (CONANP) are acknowledged as well as the access to Parks Punta Sur and Chankanaab by Foundation of Parks and Museums of Cozumel (FPyMC) and Parks Xcaret and Xel-Há. The authors appreciate the support, services and knowledge sharing to the project given by the Cooperative Society of Fishing Production of Cozumel [Sociedad Cooperativa de Producción Pesquera Cozumel].

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