Initial estimate of kinetic energy of tidal currents in the province of Chubut, Argentina

Ana J. Lifschitz, Domenico P. Coiro, Giancarlo Troise, Horacio Giaquinta, Fabio Lazcano, and Norma De Cristofaro

Abstract— **This work is a preliminary study to find some sites for the potential use of tidal stream energy and their associated currents in the Chubut coast. In addition, an evaluation of the energy resource of the Chubut Gulfs is made. Among other possible technical solutions, in this work the exploitation of tidal energy is based on the use of hydrokinetic turbines, which transform the stream translational kinetic energy into rotational kinetic energy available to feed an electrical generator. The energy can be extracted analogously to that of wind energy; therefore, it is not necessary to build a dam, avoiding the environmental and economic disadvantages it represents. The total annual theoretically exploitable kinetic energy of the whole cross section at San José Gulf was estimated as 1,006 GWh/year, but assuming a device conversion efficiency of about 45%, this lowered to 453 GWh/year. Considering also some practical limitations due to the installation of multiple devices in a hypothetical farm layout, the annual available energy production for three turbines rows in the inlet of San José Gulf was 61 GWh/year. Such results were based on a preliminary analysis using a relatively small amount of data, which can give an initial estimate of the expected available resource in the area of interest. Future experimental investigations may improve the accuracy of the resource evaluation. Lower tidal kinetic energy was found in the Nuevo Gulf and at the Chubut River mouth, thus, a system to increase the flow should be considered.**

Keywords—**Hydrokinetic turbines, Tidal power, Chubut, Argentina, Resource assessment.**

I. Introduction

Tidal seawater power, which results from the gravitational force between moon, earth and sun, is one of the major renewable energy sources [1-4]. The world theoretical potential of tidal energy, including tidal currents near shorelines has been estimated at around 1,200 TWh / year [5]. The global energy resource of the oceans is enormous, far exceeding global energy demand [5].

There are currently two different ways to harness energy from the tidal resource. One type uses a structure similar to a dam, the system works analogously to a conventional hydroelectric power station exploiting the potential energy from the available tidal range. Although this kind of systems show a high energy potential, there are significant environmental implications that hinder their implementation [6]. Another alternative production is to harness the kinetic energy of the currents ("tidal currents"). The level variations produced from the movement of the tides generate incomes and discharges of large bodies of water within the natural enclosure, promoting ebb and flow currents of great magnitude. The kinetic energy that this phenomenon possesses can be transformed into mechanical energy and then converted into electrical energy by means of hydrokinetic turbines (H.K.T.). These devices work using the same principles of wind turbines, sharing similar design philosophies [7-9].

Energy from tidal currents has two great advantages over other renewables: a high load factors resulting from the fluid properties and the predictable resource. This type of renewable energy has the advantage of being anticipated, although with certain degree of uncertainty. The net movement of water includes not only the periodic flow due to tides, but also a flow known as residual circulation [10]. These components are random in nature. The main agents responsible for this residual flow is the non-linear interaction of the flow with coastal geometry, irregular bottom topography and friction, large-scale turbulence, and spatially variable eddies and wave-current interactions. [10]. Various research, through

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numerical modelling, have studied tidal propagation in the region. Mazio et al. (2004) [11], applied a non-linear, two-dimensional tidal model at Nuevo Gulf and the adjacent continental shelf. They concluded, after comparing the model results with tidal amplitudes observed inside the gulf, that the semidiurnal tide accounted for almost 90% of the total tidal energy. Glorioso and Flather (1997) [12] came to the same conclusion: the energy flux due to the semidiurnal dominated, being two orders of magnitude larger than the ones due to the other tidal constituents. Palma et al 2004 [13] used the Princeton Ocean Model (POM) on the Patagonian shelf. The tidal experiments showed the dominance of the semidiurnal component. Although there were only limited in situ observations to compare the model with, the author determined that there was general agreement between the semidiurnal currents predicted by the model and those determined from current meter observations. The non-linear interaction between the tidal currents and the bottom topography in the model leaded to the formation of tidal fronts near the Valdés Peninsula. Several studies have shown, however, that the accuracy of low-resolution numerical models of the Patagonian Shelf are still unsatisfactory [14, 15]. Moreira et al. (2011) [16] suggested that the models used did not have appropriate horizontal resolutions in order to well represent the bathymetric features of the gulfs, which determine tidal propagation in their interiors. They [16] applied a set of three nested high-resolution models based on the Hamburg shelf ocean Model (HamSOM) and reached to the conclusion that little energy flows into Nuevo and San José Gulfs, consistent with the low speeds suggested in their interior, by the semidiurnal tidal current ellipses derived from the three nested models. According to the authors, the narrow mouths of the San José and Nuevo Gulfs restrict energy flow into their interiors. Tonini and Palma (2017) [15] applied a three- dimensional regional model in the region: they found that tidal currents are also larger for the semidiurnal constituents particularly southeast of Valdés Península and at the entrance of the gulfs (modelled current up to 2- 2.5 m/s, Fig. 1).

Unfortunately, as pointed out by Palma et al. (2004) [13], there is not enough direct observational evidence in the region to contrast numerical results, only short time series of current measurements in specific places. As a result, little is known yet about tidal currents, the nonlinear interactions that probably occur in the area, because of the complex geometry and bathymetry, and the energy dissipation in the region. However, according to [10], the magnitudes of the residual current are between one and two orders of magnitude lower than the currents due to tides. Moreira et al. (2011) [16] defined this site as a macrotidal system where tidal currents tend to be larger than residual currents, making the periodic flow continue to be a predictable source. This advantage represents technological benefits in terms of power generation, energy supply planning and network flows structures.

On the other hand, ocean energy devices are subjected to hostile, corrosive, marine environments and require continuous preventive maintenance to ensure prolonged and safe operation. Installation, operation and maintenance of energy devices are relatively expensive [6]. Maintenance costs will be high as for any other off- shore technology and have a high share of lifetime costs. It is estimated that annual operation and maintenance costs of ocean energy devices can be as high as about 3.4–5.8% of capital expenditure compared to 2.3– 3.7% for off shore wind [17].

Another aspect to consider is the impact from H.K.T. arrays on the hydrodynamic characteristic of the marine environment [6]. The flow and the level of the water could be altered, including a decrease in the tidal range and a delay in high and low tides [18]. It has to be noted, however, that the array configuration will be dependent on the energy device or technology and the area chosen for H.K.T. installation. On the other hand, the work carried out by Ahmadian and Falconer [19] on the Severn Estuary and the Bristol Channel, concluded that the layout of a turbine array could produce impacts on power output and, to a lesser degree, on the hydrodynamic characteristic of the environment.

Although the generation of energy using tidal currents is generally diffuse around the world, it is concentrated at a number of sites. The reason of this distribution is in part, due to geographic effects produced by the presence of continents, islands coastlines, and depth variation, which modify the response of the oceanic waters to the astronomic tide generation forces. Tidal resources are generally high in areas where a good tidal range exists, and also where the velocity of the currents are amplified by the funnelling effect, produced by coastline and seabed in narrow inlets and straits, in channels between islands, etc.

Argentina has a coastline of 5,117 km and an oceanic strip with an area of 960,000 km^2, from the Río de la Plata to the Malvinas Islands, which is considered one of the largest in the world. The evaluation of the resource is essential for an adequate selection of places and definition of the characteristics of the equipment. It is possible to define a potential scenario for the energy use sustained both in tides, as in the currents associated. The tidal phenomenon is important from South of San Matias Gulf to Tierra del Fuego with high current intensities exceeding 1.5 m/s [20], creating hopes of taking advantage of this potential energy at low cost. This feature has awakened a singular interest in natural possibilities that the country has for electricity generation and it is increasingly recognised the need to exploit the marine energy. Although there are clear indications of high potentials from Patagonian tidal phenomenon for energy purposes [20-23], nowadays there is a great lack of data to support fully development of an energy generation at a commercial phase. Existing data is mainly for tidal heights, however there are few, isolated values of current velocities, since tidal height data for specific locations is obtainable

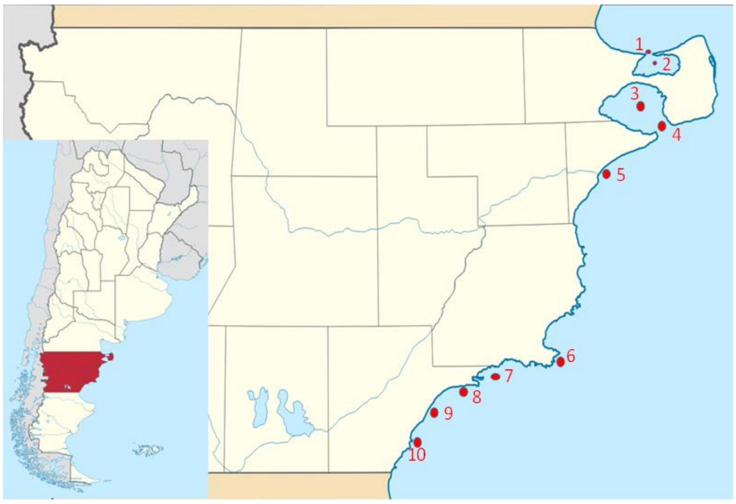

Fig. 1. Tidal currents velocity and depth along the Chubut coast. The red points mark the places where tidal currents velocity and depth are known [20, 21]. Find references of this Fig. in Table I.

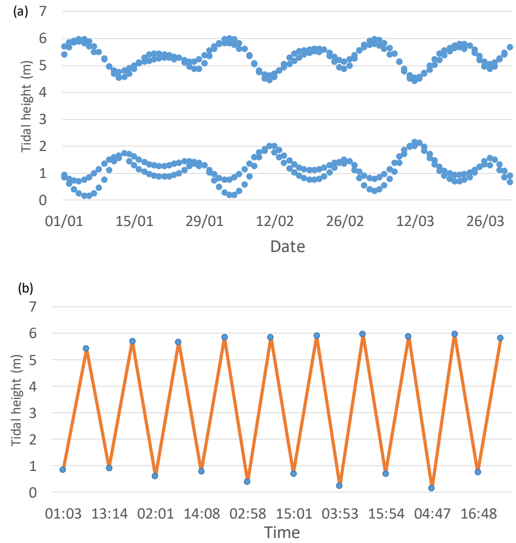

Fig. 2 (a). Tidal height measurements (m) with pressure gauge at Puerto Madryn, January-February-March 2018 period. Fig. 2(b). Tidal height measurements (m) for a short period of Fig. 2(a), from January 1 to 5, 2018 [22].

TABLE I
REFERENCES OF FIG. 1. SITES ON THE CHUBUT COAST WITH TIDAL CURRENT VELOCITY AND DEPTH.

Name (number)	Velocity Max (m/s)	Depth (m)
San José Gulf inlet (1)	3	130
San José Gulf interior (2)	0.3	60
Nuevo Gulf interior (3)	< 0.2-0.3	150
Nuevo Gulf inlet (4)	0.8	120
Chubut River (5)	0.9	2
Leones Island (6)	2.5	22
Bustamante Bay (7)	0.2	<20
Aristizabal lighthouse (8)	0.3	20
Solano Bay (9)	0.2	16
Comodoro Rivadavia Harbour (10)	0.3	36

through the Servicio de Hidrografia Naval, (henceforth S.H.N.) tide tables. On the other hand, maximum current velocities and surface intensities are available for a smaller number of sites. Even more, there is no systematic measurements of this parameter at the Chubut coastline. Extractable power estimation are possible at an average preliminary value, creating the base for further research.

The purpose of this work is to discuss the characteristics of tides in some places within the Chubut coast (Argentina), estimating the theoretical power of the tidal currents in order to select sites to install hydrokinetic turbines. Particularly, an estimation of the expected energy production in the site of San José Gulf is proposed.

II. TIDAL RESOURCE AND DATA COLLECTION IN CHUBUT COAST, ARGENTINA

A. *Tidal resource*

The main tide affecting the region of interest (Fig. 1, references in Table I), is the semidiurnal component, [24] with two high tide and two low tide in the day, spanning 6 h from each other. The slack water (defined as a short period with no movement either way in the tidal stream), ranges from a few minutes to an hour, during which the currents are practically zero. Shortly before the slack water, tidal currents gradually weaken in intensity, and then progressively increase until reaching maximum magnitudes with a course change of approximately 180°. Consequently, tidal current presents a cyclic temporal variability, a situation that leads to think of devices that could operate in a current direction, during the rising tide process, and in the opposite direction, during its descent. This type of operation is achieved in two ways: using reversible blades or adjustable pitch, or turning the turbine orientation completely according to the tidal direction.

In addition to the daily cycle, there is a monthly cycle related to Earth-Moon-Sun system relative positions. The monthly cycle gives rise to spring and neap tides. Spring tide is the very highest and very lowest tide (i.e. the largest tidal range) which occurs twice a month (every 14/15 days) with lunar new and full phases, with greatest current intensities. Neap tides are the opposite of the spring tide, where minimum amplitudes with lower intensities occur. Tidal height measurements with pressure gauge at Puerto Madryn, from January to March 2018 period can be observed in Fig. 2a, [22]. Fig. 2b. shows a short period (five days) of Fig. 2a.

Fig. 3. Valdés Peninsula (Chubut). The dark brown area shows the Wildlife Reserve Area [29].

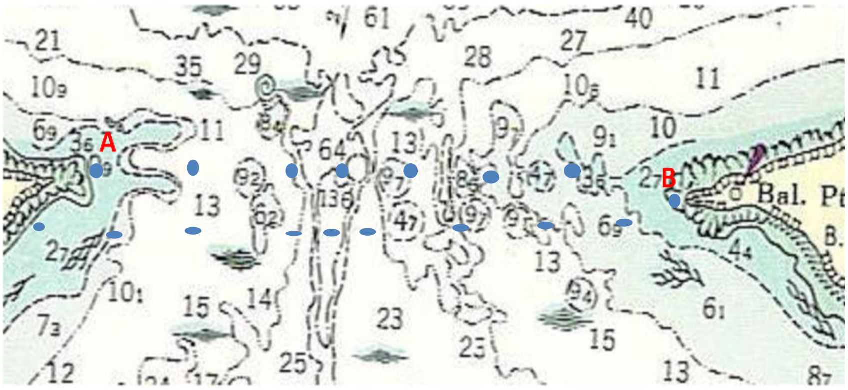

Fig.4. San José Gulf entrance [35]. The letter A marks the western edge of the mouth Punta Quiroga, and the letter B marks its eastern edge Punta Buenos Aires. The blue dots mark the points where the depths were registered for velocity estimates.

B. Data collection

The information obtained was extracted from different methods: the S.H.N. database, from nautical charts and from data supplied by provincial authorities, in situ inspections, measurements and velocities estimations. The S.H.N. has current records that date from the 1960s and 1970s to the present. This information was used to select strategic sites for tidal currents harness. Based on the field information plus bathymetry obtained from nautical charts, Dragani et al. [21] and Lifschitz et al. [20] carried out a synthetic analysis of the currents along the Argentinean coast, between the coasts and the 15/20 m isobaths. The work was focused on collecting data on two of the main parameters that characterize a site for the installation of a hydrokinetic turbine: tidal current speed and depth. Fig. 1 shows data along the Chubut coast (find references of this Fig. in Table I). Although the considered depth range is relatively lower compared to typical tidal installations [25], the results are considered useful for the purpose of this work.

C. Potential sites to harness tidal currents at Chubut coast.

Three sites situated to the north of Chubut River were chosen; San José and Nuevo Gulfs inlets (Peninsula Valdés) and the Chubut river mouth at Rawson harbour.

1) Tides and currents at the Peninsula Valdés

In the 1960s, the Valdés Peninsula, located in the northeast area of Chubut, was the focus for several tidal stream energy exploitation projects. This peninsula is surrounded by the San José Gulf, to the north, fed by the San Matias Gulf, and the Nuevo Gulf, to the south, fed by the Atlantic Ocean. The Ameghino isthmus connects the mentioned peninsula with the mainland (Fig. 3).

In addition to the substantial high tidal range, the topography disrupts the propagation of the marine currents producing constant time lag in height between tides in Nuevo Gulf and San José Gulf. This difference could reach about 4.5 m, whereas the differences in time are about 3 h 50 min at low tide and 4 h 30 min at high tide [11]. Thus, when the surface elevation in one gulf is close to high tide, in the other one it is close to low tide and reciprocally. Several projects to build a tidal power station taking full advantage of the difference have been discussed in the past. The basic idea of these projects was to build an artificial channel through the Ameghino isthmus to let the water flow between both gulfs, and to install a tidal power station at the channel, that would work with the tidal potential energy, similar to hydroelectric power station. However, none of the projects progressed, to some degree, due to high investment costs [26, 27]. Strong environmental impacts have been pointed out regarding a tidal power project in the isthmus. The volume flow of water in the channel used to drive the turbines would be particularly important, affecting the tidal regime itself. Another objection regards the ecological impact that the mixing of the waters of both gulfs, with different physical properties [28], might produce on their respective biotas. Peninsula Valdés was declared a Wildlife Reserve in 1999 (Fig. 3, [29]).

In hydrokinetic turbines, the energy is extracted in a similar way to that of wind energy, it is not necessary to build a dam, in this way the environmental and economic inconveniences that it represents are avoided. The absence of dams allows fish and aquatic communities to pass these structures by swimming around them, thereby avoiding what is widely perceived as the primary environmental impact of hydroelectric generation [30]. For the case of strong currents in a channel leading into a basin with a large tidal range, Garrett & Cummins 2013 [31] conclude that the maximum power available using a ‘fence’ of turbines occupying the whole cross-section of the channel, is comparable with the power using a barrage. Vennell (2010) [32] determined that in order to maximise turbine efficiency (or minimise the required number of turbines), the farm must be configured to occupy the largest fraction of a channel’s cross-section permitted by navigational and environmental constraints. Many authors underline that there is still much to be done in evaluating the use of H.K.T.s in tidal channels with strong currents [31, 33, 34]. In any case, the installation of H.K.T.s in this area is a

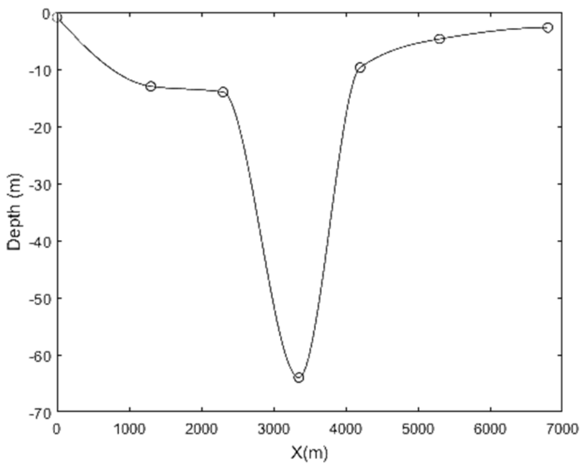

Fig. 5. Depth distribution (m) at the entrance of the San José Gulf as a function of the distance along this line $\overline{AB}$ in Fig. 4 (depths referred to the lower limit of the mean low neap tides, according to SHN [35] (last update 2015-06-24).

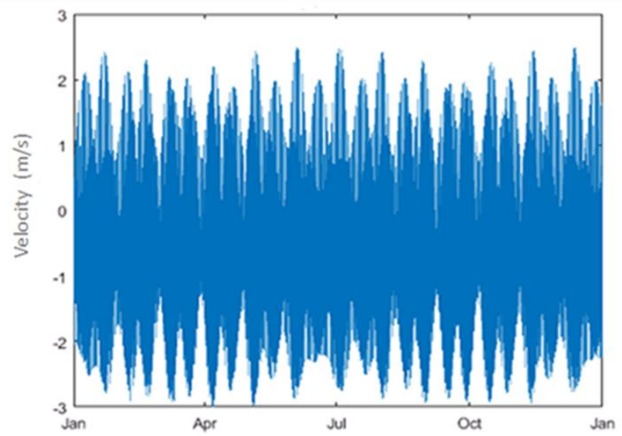

Fig. 6. Assumed yearly time series of the current velocity (m/s) at water surface (based on trend data (2004) for another similar site, [37].

matter of complexity and other aspects such as noise and vibrations should be studied.

2) Tides and currents at the San José Gulf

The surface currents are very intense at the mouth of the San José Gulf, being able to reach almost 3 m/s during spring tides near its western edge Punta Quiroga [35]. Tonini et al. [23] also mentioned a current value of 3 m/s in the zone. On the eastern edge, (Punta Buenos Aires), intensities could reach to 0.6 m/s. Inside the Gulf, the superficial currents are considerably reduced and they do not exceed 0.30 m/s [35]. Dragani [36] made current measurements in the interior of the San José Gulf, precisely at Bengoa beach on the eastern side, with an AANDERAA RCM9 current meter, resulting in a mean value of 0.1 m/s. In this work, particularly, a simplified estimation of velocity profile at the entrance of San José Gulf (Fig. 4) is proposed. The depth profile along the line indicated as $\overline{AB}$ in Fig. 4 is reported in Fig. 5 as a function of the distance along this line.

A maximum depth of about 68 m is reached close to the centre of the line. The maximum assumed current speed is considered equal to V_{max}=3 m/s. An approach based on the time integration of the water current kinetic power has been used to estimate the available resource at the San Jose Gulf site. Such estimation method requires the knowledge of the time history of the current speed over a yearly time interval. The available data comprised only the value of the observed peak current speed. Therefore, a synthetic time history of the flow speed has been estimated by scaling, with respect to the peak value, a current speed time history available for a different site (the Messina Strait) since it has similar characteristics. Comparability between the two sites is based on their geographical characteristics, being both straits connecting two relatively large basins, with a current regime mainly governed by semidiurnal tidal phenomenon.

In lack of more specific time histories of the current speed, a daily velocity profile, typical of this type of tidal current, has been assumed and its maximum and minimum speeds variation have been taken according to monthly variations of lunar phases leading to the yearly time series reported in the Fig. 6.

3) Tides and currents at the Nuevo Gulf

The surface currents at the mouth of the Nuevo Gulf (Punta Ninfas) can reach 0.80 m/s in conditions of spring tides, according to S.H.N. Surface velocities are drastically reduced towards interior of the Gulf and do not exceed 0.20- 0.30 m/s. An approach proposed by [38] has been implemented in order to evaluate the superficial current intensities in the Gulf inlet. This methodology consists of approximating the velocity in the inlet using the tidal heights and periods recollected inside the Gulf, in this case at Puerto Madryn pier (Fig. 3) and considering topographic characteristics. Tidal heights and periods for 2018 at Puerto Madryn pier were also recollected from the S.H.N. web page. The approach proposed by [38], applies the following calculations:

The ascendant / descendent range (Rim) and period (Dim) were calculated using sea level data for each hour, and the amount of water entering/leaving the gulf (Via) is:

$$V_{ia} = R_{im}.A_e \quad (1)$$

where Ae, the gulf area, is 2.44x109 m2 [28]. Then, the average flow (Fim) is:

$$F_{im} = \frac{V_{ia}}{D_{im}} \quad (2)$$

The flow speed at the gulf inlet could be estimated through:

$$V = \frac{F_{im}}{S_t} \quad (3)$$

where St is the cross-sectional area, adopting an inverted trapezoidal shape, where the base is the narrower width, 16 km with a maximum depth of 100 m approx. [22]. Fig. 7 shows the velocity calculation with an overall average magnitude of 0.57 m/s. these estimates are in agreement

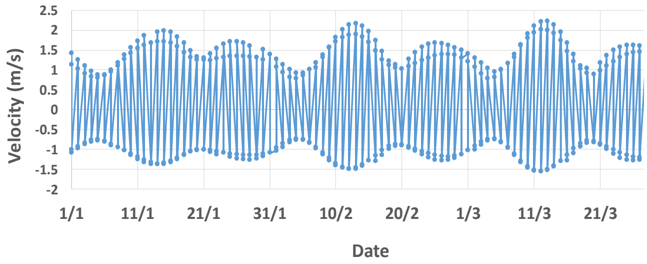

Fig.7. Velocity currents at Nuevo Gulf inlet. January-February-March, 2018 period [22]. The speed calculations were performed following the methodology proposed by [38].

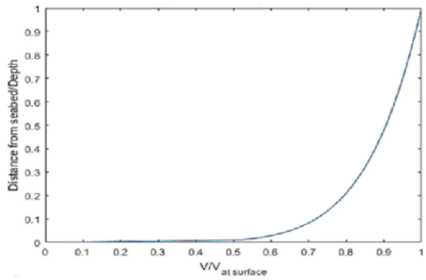

Fig. 8 Current velocity profile (non-dimensionalized with respect to the surface velocity) with depth (non-dimensionalized with respect to depth). Assumed velocity profile used in the theoretical estimations of tidal kinetic energy at San Jose Gulf.

with a short data measured by S.H.N. at the gulf inlet (1991), with an average velocity of the same order (0.34 m/s-averaged speed).

4) Tides and currents at the Chubut River mouth

The Chubut River is the most important watercourse in the province of Chubut. It has its origin in the Andes Mountain, and flows into the Atlantic Ocean forming a mesomareal coastal plain estuary (Fig. 1). The discharge of the river is strongly influenced by the tidal regime up to 10 km upstream from its mouth [39], particularly at high tides and during periods of spring tides. The interface between tides and the river discharge control the flow at the river mouth estuary. The tide regime is semidiurnal, with an average tidal range of 4.95 m in spring tides and 3.44 m in neap tides [40]. In normal weather conditions, a tidal front enters the estuary interacting with the river water. The difference in density between both media produces a salt wedge stratification, which is associated with the energy transfer. The entry of the wedge reduces the discharge and raises the level of the river. After the high slack water occurs, the tide begins to withdraw; the river discharge overflows the densest waters, affecting stratification. This complex interaction regulates the displacement of water and therefore the flows of salt, nutrients and sediments that enter and leave the estuary daily. Normally, the river drains 40 m^3/s; however, during rising tides, its drain is delayed. On the contrary, at low tide, the river drains rapidly with flows between 300 – 350 m^3/s [41]. The Rawson City Government considered the construction of a bridge and a tidal dam in the Chubut River estuary. The project envisaged the placement of two turbines that would generate 10 MW. Until now, only the bridge has been built [42], leaving the opportunity for a turbine emplacement instead of a dam.

Surface velocities measurements were carried out at the mouth of the river using spherical floats under rising and falling tides, capturing the greatest intensities between both conditions. For this purpose, two cross sections were selected along a reach of the straight zone of the river. The sections were far enough from the line coast in order to accurately measure the time it took the float to pass from one cross section to the other. Buchanan and Somers [43] documented this method as an alternative way of estimating surface flow velocities in the passage of a river. The floats were slightly submerged and there was no influence of wind or wind waves during the campaigns, (September 15 and December 15, 2018), wind velocities were under 20 km/h, and wind wave heights outside the harbour were less than 0.75 m [44]. Under these conditions, float measurements have an accuracy within 10 %. Current velocities of 0.6 ± 0.1 and 0.9 ± 0.1 m/s were collected on September and December 2018 respectively, during falling tides. During rising tides, estimations were under 0.2 m/s.

III. Calculation and Analysis of the Theoretical and Exploitable Tidal Current Power.

A. Tidal kinetic energy estimations at selected locations.

1) Tidal kinetic energy at San José Gulf

The theoretical estimation of tidal kinetic energy was carried out at San José Gulf. According to [45], the maximum flow speed is not generally accepted as enough to characterize the resource, as a consequence, a velocity spatial-temporal profile was used in order to estimate the available kinetic power. At the San José Gulf entrance cross section, the power was estimated by assuming a velocity profile with depth as a power law, specifically, considering a 1/7 exponent:

$$V/V_{\max} = (h/D)^{1/7} \tag{4}$$

where V is the current speed at the generic depth, Vmax is the maximum velocity, h is the distance from sea bottom and D is the maximum water depth. Such profile law is indicated in some marine standards, like "DNV Environmental Conditions and Environmental Loads" [46].

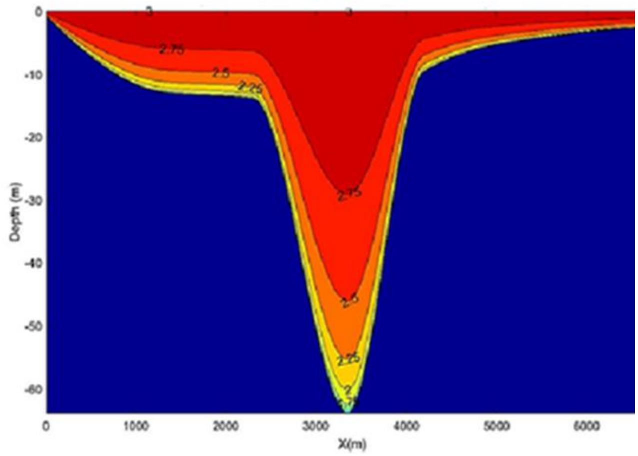

Fig. 9 Assumed velocity contour (m/s) with depth (m) over the entre cross section at San José Gulf.

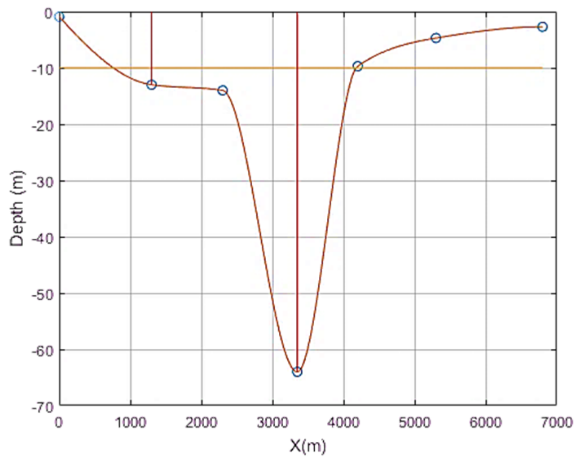

Fig. 10. Available lateral space for turbine installation. The two vertical lines represent the lateral limits of the considered area. (The circles represent points in which depth data are available, while the rest of the depth profile is obtained only by spline interpolation and is not accurately known).

Fig. 8 displays the assumed velocity profile with depth. This part of the analysis was intended to estimate a spatial distribution of the current speed in a section of the tidal current flow. The time variation of the current speed could be obtained using experimental data or data deriving from a calculation/simulation model. In the case of S. Jose gulf, there was not such data, so a time history related to a different site was used as an approximation of the current speed at the water surface in time. The place selected was the Messina Strait, where the maximum speed was similar for the two sites and the overall geographic characteristics of the two site was approximately comparable as well: both sites showed a restriction of the current flow section, as indicated above. The reference data was obtained from the Italian Navy Tidal Tables [47], which gives the values of current speed at the four daily peaks and the times of slack water, for a whole year at intervals of about 3 hours, with some variations in the time intervals due to the oscillations in the peak and slack water times. The original data was interpolated in time, to have a more detailed time series. The tidal tables suggest to use a sinusoidal interpolation between the known points. The data taken from the reference site has been used as 'shape' for the variation in time of the effective site of interest.

Based on the assumed velocity profile with depth (reported in Fig. 8) and on the known seabed profile, a current speed field was estimated over the entire cross section of the considered site, as reported in the Fig. 9. It is also assumed that the velocity distribution at the surface is uniform across the entrance. Based on the above assumptions, the assumed spatial distribution of the velocity field can be determined and integrated over the cross section S_t, at each time, in order to obtain the total kinetic power available in the flow:

$$P_s(t) = \int_{S_t} \frac{1}{2}\rho V^3 dS_t \qquad (5)$$

where ρ is the water density, V the current speed, S_t the area of the current flow cross section and P_S the theoretical kinetic power in the entire section, [48].

2) Estimation of the available energy for the entire cross section at San José Gulf

The total power described in the preceding section is purely theoretical and represent the amount of energy contained in the water flow field. The available kinetic power is constrained by the theoretical Betz limit, which sets a threshold to the useful kinetic power approximately equal to the 59% of the entire kinetic power of the flow. Moreover, the effective efficiency of real turbine is generally lower than the theoretical Betz limit.

Recalling the definition of power coefficient of a tidal stream turbine as:

$$C_P = \frac{2\,P_t}{\rho S_d\, V^3} \qquad (6)$$

where P_t is the turbine output power and S_d is the turbine disk area, a typical value of the power coefficient is assumed equal to $C_P = 0.45$. The value of the power coefficient is strongly dependent on the type of tidal stream device used for energy conversion and on the specific characteristics of the installed device. The value of the C_P assumed in this work is based on experimental data observed in towing tank tests on a small model of a 3-bladed hydrokinetic turbine, as reported in [37]. This prototype was a twisted blade horizontal axis turbine of root chord 0.136 m; tip chord: 0.05 m and radius 0.4 m.

The total annual kinetic energy available in the whole section of the site was estimated as:

$$E_{a0} = \int_0^Y P_S(t)dt \qquad (7)$$

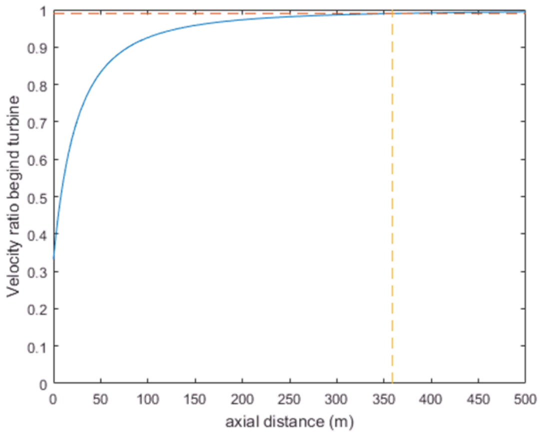

Fig. 11. Trend of the wake velocity loss in function of the distance behind the turbine, assuming a wake decay factor k_w=0.05. (The vertical line indicates a recovery of 99% of the undisturbed current speed).

TABLE II
ANNUAL ENERGY PRODUCTION AND ASSUMED POWER COEFFICIENT FOR SAN JOSÉ GULF.

Description	Annual energy production (GWh/year)	Assumed power coefficient
Theoretical total flow kinetic energy	1,006	
Betz limited theoretical total flow kinetic energy	594	0.59
Total flow kinetic energy for CP=0.45	453	0.45
First turbine row energy production	21	0.45
Second turbine row energy production	20.3	0.45
Energy of three turbine rows	61	0.45

where Y represents the period (1 year in this case). The Betz limited theoretical extractable energy is equal to $E_{a,\ Betz} = 0.59E_{a0}$. While, considering a power coefficient of $C_P = 0.45$, the amount of annual available energy in the current flow is equal to $E_{a,\ C_P=0.45} = 0.45\ E_{a0}$.

3) Estimation of the available tidal stream energy for an array of turbines at San José Gulf

The conversion of the kinetic energy into electricity can be made by intercepting the flow via arrays of H.K.T. [49]. These turbines extract kinetic energy from marine currents, converting them into mechanical power without interrupting the natural flow. For the case of the mouth of San José Gulf where high speeds of tidal currents are registered, a different type of estimation of the available power is reported, based on considering an array of turbines composing a hypothetical tidal farm (farm approach). In this approach, the turbine radius is equal to $R = 2.5$ m (diameter D= 5 m) . The width of the area available for the installation of the turbines, excluding areas with depth below 10 m, is equal to $available\ lateral\ distance = 2050$ m . In such space, assuming a lateral spacing between the turbines equal to a given multiple of the turbine diameter D, only a limited number N_{turb} of turbines can be installed. In this study, a lateral spacing equal to three diameters has been assumed. Consequently, the number of deployable turbines is N_{turb}=136. Fig. 10 shows the available lateral spacing for turbine installation, with the number of deployable turbines of N_{turb}=136.

An operating depth of about 10 m was assumed and with a power coefficient of 0.45, it is possible to estimate the annual energy production. In order to assess the local energy resource, it is also assumed that the produced power for each turbine varies with a simple cubic law as a function of the current speed, without considering the power limitation due to the characteristics of the electrical generator for a specific device. This assumption has been made in order to avoid the dependence of the energy production estimation on the machine size and generator performance, aiming at a preliminary resource assessment independent of device specific parameters. The only machine dependent assumptions in this study are related to the size of the turbine and to the assumed power coefficient. If there is more than one row of turbines, the wake effects could be important and must be consider, according to some CFD (Computational Fluid Dynamic) studies reported in [50, 51]. Garrett & Cummins (2007) [52] stressed the importance of the wake dissipation in a channel, which makes the power available for electricity production been smaller than the channel's potential, (defined by the author as the maximum power lost by the flow due to the turbines).

In order to account for the wake losses, the Jensen wake model is applied. Such model assumes that the velocity in the wake follows the expression (8),

$$U/U_\infty = 1 - 1 - \sqrt{1 - C_T}/\left(1 + k_w \frac{x}{R}\right)^2 \qquad (8)$$

where x is the distance behind the turbine, R is the turbine radius, k_w is the wake decay factor and C_T the turbine thrust coefficient, defined as:

$$C_T = T/\ \frac{1}{2}\ \rho V^2 S_d \qquad (9)$$

where T is the turbine thrust. The thrust coefficient in this study is assumed constant and equal to $C_T = 0.89$. A possible value for the wake decay factor is approximately equal to $k_w = 0.05$ for tidal current turbine applications. Fig. 11 represents the trend of the wake velocity loss in function of the distance behind the turbine, assuming a k_w = 0.05.

TABLE III
MAIN PARAMETERS USED FOR NUEVO GULF INLET AND CHUBUT RIVER MOUTH POWER OUTPUT CALCULATION.

	Nuevo Gulf inlet	Chubut River mouth
Mean velocity (m/s)	0.57	0.55
Cross-section area (m^2)	8.9E5 (trapezoidal)	40 (rectangular)
Density (kg/m^3)	1025.85	1019.26
Power (MW/km)	5.7	< 0.04

TABLE IV
ASSUMPTIONS MADE IN THIS STUDY FOR SAN JOSÉ GULF

Farm approach	Assumptions
Turbine characteristic	Specific size of the turbine R=2.5 m
	Power coefficient: 0.45
	Limitations of the specific electrical generator are not considered
Wake effects (Jensen model)	Wake decay factor: 0.05
	Thrust coefficient, constant: C_T=0.89
Produced power	Lateral spacing between turbines: 3 diameters
	Operating depth: 10 m
	Variation with the cubic law as a function of the current speed

If the entire cross section at San José Gulf is considered, the total annual kinetic energy of the whole section available in the current of the site is estimated as E_{a0}=1,006 GWh/year. The Betz limited theoretical energy is equal to $E_{a,\ C_P=0.59} = 0.59\, E_{a0} = 594$ GWh/year. Lastly, with a power coefficient of $C_P = 0.45$, assuming a conversion efficiency of about 45%, the amount of annual available energy in the current flow is equal to $E_{a,\ C_P=0.45} = 0.45\, E_{a0} = 453$ GWh/year. In the case of the available energy for an array of turbines, the energy of a single row of turbines is equal to $E_{t1} = 21$ GWh/year. According to this formulation, with a turbine radius equal to R=2.5 m, to obtain a 99% recovery of the current speed, a spacing between two consecutive turbines of about 360 m is required. Considering the cubic relation between speed and power, a 1% loss in velocity is approximately associated to a 3% loss in power. Assuming that the velocity profiles for the other rows is similar to that of the first row, the total energy generated by 3 consecutive rows of turbines, spaced between each other by 360 m (with 136 units on each row), is estimated as:

$$E_{t3} = E_{t1}\left(1 + (1 - 3\%) + (1 - 6\%)\right) = \\ = 61 \text{ GWh/year} \quad (10)$$

where E_{t3} represents the energy of three turbine rows and E_{t1} is the energy of one turbine row. The annual available energy production for three turbines rows in the inlet of San José Gulf was 61 GWh/year. A summary of estimated energy production is reported in Table II for the San José Gulf.

4) *Tidal kinetic energy at Nuevo Gulf and Chubut River mouth*

Equation 5 describes the hydrokinetic power density value of the fluid. If the currents at the mouth of the enclosure are constant and the normal area of the channel St is constant too, (5) results in:

$$P_s = \frac{1}{2} \rho\, S_t\, V^3 \quad (11)$$

The cross-section S_t has a trapezoidal shape at the gulf inlet and it is rectangular for the Chubut river discharge.

The assumptions made result in an overestimation of the resource (according to [38]), at the entrance of the Nuevo Gulf, where a mean flow estimated was 0.57 m/s and the wide channel is 16 km [28]. The obtained power turned out to be 5.7 MW/km. At the Chubut river mouth, using a density=1019.26 kg/m^3, mean speed flow= 0.55 m/s and cross section area of 40 m^2 power less than 0.04 MW/km is calculated.

To be economically feasible, several studies recommend installing tidal-stream energy devices in places where tidal-stream velocities are above a minimum value. For most of the scientific community, this value ranges from 1.5 to 2.5 m/s. Polo et al. [53] indicates a value greater than 2 m/s. The Electric Power Research Institute [54] recommends places with maximum flows greater than 1.5 m/s; likewise [55] the appropriate places are those that present spring average currents of at least 2-2.5 m/s. With the advance of new technology development, lower velocities, less than 1m/s, could be considered to ensure that the system is capable of delivering power efficiently over a wide range of current velocities. Thomas et al. [56] studied the effect of the diffuser in a towing tank which effect was to increase the power output. Turbines operating inside a converging/diverging nozzle or duct are sometimes introduced as means to increase the power output of similarly sized rotor devices deployed in relatively low speed/low-energy currents. The incorporation of the shrouding device is believed to enhance the turbine efficiency [57]. Several authors have studied the effect of implementing a diffuser to maximise the output power [58-64]. The improvement of the performance is obtained essentially by increasing the mass flow passing across the rotor and also with a limited increasing of speed. These improvements can be obtained using a divergent shape, with a duct exit area larger than the section area at the turbine location. According to [18], a significant increase in the power output can be observed for a diffuser augmented turbine, but at the price of a significantly larger frontal size and a significant increase in the thrust acting on the shroud-turbine assembly.

Due to the lower speeds of tidal currents found in the Nuevo Gulf and Chubut River mouth, it would be necessary to implement the technology previously descripted. However, to assess the overall effectiveness of the diffuser augmented solution in an economic analysis, it has to be considered also the additional cost of the added structural components (the diffuser and the related support structures). Moreover, the possible larger thrust on the whole system, due to the diffuser, can introduce structural and dynamic problems, also requiring more expensive structure.

Table III summarises the results power output and main parameters for the Nuevo Gulf and Chubut river mouth, and the assumptions made in this study for San José Gulf are shown in Table IV.

It has to be noted that, in order to avoid the dependence on the characteristics of a specific machine, to give an estimation of the potential resource of the considered area without the influence of the choice of a particular hydrokinetic turbine, the rated power was not explicitly considered in the analyses based on a simulated hypothetical tidal farm.

IV. Conclusions

The aim of this work was to provide a preliminary estimation of the tidal energy resource available in the coast of Chubut, Argentina. In addition, the theoretical extractable power by means of hydrokinetic turbines was assessed. The coast of Chubut presents an area of high-energy potential located at the mouth of the San José Gulf. A preliminary estimation of the available resource has been performed. Assuming a conversion efficiency of about 45%, for the considered hydrokinetic turbine devices, the estimated exploitable annual energy resource is about 453 GWh/year, theoretically considering the whole cross-section of the gulf entrance. When some practical limitations to the installation of a hypothetical farm layout are also considered, the amount of expected production is consequently reduced. The annual available energy production for three turbines rows in the inlet of San José Gulf was estimated to be 61 GWh/year. To confirm such estimation detailed experimental measurements are needed. Lower tidal kinetic energy was estimated for the case of Nuevo Gulf and Chubut River mouth, consequently, a system to increase the flow should be considered to ensure that the hydrokinetic turbine is capable of delivering power efficiently over a wide range of current velocities. Even though the results presented in this paper have significantly improved our understanding of tidal kinetic energy in this region, and the power output estimated is consistent with the aim of this work, the collection of more observations, particularly in the interior and at the mouths of the Gulfs, is necessary to develop and fully shape tidal potential into power generation in the region.

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