EasyChair Preprint

№ 15349

Performance Assessment of Hydrokinetic Turbines - Case Study in the Boqueirão Channel

Anna Dulce Espíndola, Osvaldo Ronald Saavedra,
Pedro Bezerra Leite Neto and Denisson Queiroz Oliveira

EasyChair preprints are intended for rapid dissemination of research results and are integrated with the rest of EasyChair.

November 1, 2024

Performance Assessment of Hydrokinetic Turbines - Case study in the Boqueirão Channel

Anna D. Espindola * **Osvaldo R. Saavedra** * **Pedro B. Leite Neto** *
Denisson Q. Oliveira *

* *Universidade Federal do Maranhão, MA, (e-mail: anna.dulce@discente.ufma.br, o.saavedra@ieee.org, pedro.neto@ufma.br, dq.oliveira@ufma.br).*

Abstract: Tidal energy has a low-frequency intermittent behavior and its predictability is guaranteed because it is related to astronomical phenomena. The North and Northeast regions have the largest tidal ranges on the Brazilian coast, ranging from 6 to 10 meters. In this article, a comparative performance's study of three configurations of a commercial hydrokinetic turbine, when subjected to the annual tidal profile observed in the Boqueirão Channel, using performance metrics based on the total energy production. The commercial turbine Tocardo T1, whose rotor diameter is 6.3 m, presented the highest productive energy in the area, since about 42% of the speeds are in a range close to its nominal speed.

Resumo: A energia proveniente das marés possui caráter intermitente de baixa frequência e sua previsibilidade é garantida por estar relacionada à fenômenos astronômicos. As regiões Norte e Nordeste possuem as maiores amplitudes de maré da costa brasileira, podendo variar de 6 a 10 metros. Neste artigo é realizado um estudo comparativo do desempenho de três configurações de uma turbina hidrocinética comercial, quando submetidas ao perfil de maré anual observado no Canal do Boqueirão, utilizando métricas de desempenho baseadas na produção total de energia. A turbina comercial Tocardo T1, cujo diâmetro do rotor é 6,3 m, apresentou a maior energia produtiva da área, uma vez que cerca de 42% das velocidades encontram-se em uma faixa próxima a sua velocidade nominal.

Keywords: Hydrokinetic turbine; Boqueirão Channel; Tidal energy; Performance analysis.

Palavras-chaves: Turbina hidrocinética; Canal do Boqueirão; Energia de maré; Análise de desempenho.

1. INTRODUCTION

Ocean energy has a promising future due to its high theoretical energetic potential, greater predictability of its behavior and relative ease of integration into the electrical system. As it is a renewable and clean source, it does not directly pollute the environment and its primary source is found in abundance in nature. This form of generation does not emit greenhouse gases and there is no need to flood areas, making it a strong candidate to participate in the green hydrogen production chain.

The largest tidal amplitudes on the Brazilian coast occur in the North and middle North regions. Studies carried out in the 1980s reveal some sites with high potential for tidal energy generation, Eletrobrás (1981). Such sites are promising for the exploration of marine renewable energies, both due to the potential energy of sea level amplitudes and the kinetic energy associated with tidal currents, Czizeweski et al. (2020). It is estimated a energetic potential of 72 TWh, with tidal differences ranging from 6 meters on the coast of Maranhão to 10 m on the coast of Amapá. Azevedo et al. (2022) assessed the potential of tidal currents in the Pará estuary, obtaining the density from 0.4 to 0.7 MWh/m^2 in a spring and neap tide cycle respectively.

A structure is needed to support tidal generation, and to take better advantage of it, it is possible to combine different forms of generation. Offshore wind power, tidal currents and wave harnessing are an example of an energy hub. According to Ortiz and Kampel (2011), the wind potential *off shore* for the entire Brazilian margin with a bathymetric interval up to 100 m in depth is 606 GW. The North and Northeast regions hold most of this potential, suggests Ortiz and Kampel (2011).

Studies that look for sites with high energy potential (*hotspots*) of tidal currents have been developed in the most places of the planet, Fouz et al. (2022) and Yang et al. (2021). The implementation of hydrokinetic turbine farms has also been studied, Ramos et al. (2014) and Wen and Lin (2022), as well as the search for new methodologies for hydrokinetic turbine design, Rezek et al. (2022). Studies seek new optimization procedures applied to hydrokinetic turbines, Gemaque et al. (2022), and application of different methods to represent horizontal axis turbines, Oliveira et al. (2023).

Typically, the dimensioning of tidal power plants has been guided by determining the average velocity of the tidal current in the proposed location. The higher the observed speed, the more power the turbine can generate. Once the average tidal stream velocity is determined, the available power that the turbine can generate is estimated. This can be done using the turbine power curve, which will show how much power can be generated at different speeds of tidal currents.

The process is refined by including any site-specific factors that may affect turbine size, such as water depth, flow direction, and turbulence. Despite being a good guide, this procedure fails to guarantee the optimality of the process, given the variability of currents during a tidal cycle and, on a larger scale, in the lunar cycle. Therefore, a sensitivity analysis of turbine sizing versus performance curve throughout the generation cycle can be an essential support for the most appropriate choice of turbine size and type.

In this article, we present a performance comparison study of a commercial turbine compatible with the physical characteristics and energy potential of the Boqueirão channel. Considering the classic average velocity criterion described above as a reference, other values (criteria) are evaluated based on the total energy produced in the estuary. The physical guarantee is determined for the turbine with the best performance.

The article's organization is as follows: Section 2 presents the hydrodynamic modeling of the Boqueirão Channel; The details of the hydrokinetic turbine modeling, performance metrics, and physical guarantee are presented in Section 3. The results of the evaluation of velocity distribution, performance of the hydrokinetic turbines, and physical guarantee are presented in Section 4. Finally, the conclusions are presented.

2. TIDE CURRENTS OF THE BOQUEIRÃO CHANNEL

The historical series of tidal velocities applied in this work was obtained through hydrodynamic simulation of the Boqueirão Channel. This location was chosen because studies point to its high energy potential from tidal currents (Czizeweski et al. (2020), Veras et al. (2021), González-Gorbeña et al. (2015)).

2.1 Characterization of the area

The São Marcos Bay is located in the state of Maranhão, in the Northeast region of Brazil, as illustrated in Figure 1. The bay is around 130 km long and stretches are over 20 km wide, housing the second largest port complex in Latin America in terms of cargo handling.

The Boqueirão Channel is inserted in the Bay of São Marcos. Located near the Ponta of Espera port terminal, this is a natural channel that separates Medo Island from Upaon-Açu Island and is around 900 meters wide and has a depth that varies between 20 and 30 m, Czizeweski et al. (2020).

2.2 Modeling of tidal currents

Measuring the tidal velocity in the region of interest would be costly, so the estimation of these tidal currents was

Figure 1. Location of the Boqueirão Channel.

carried out using the Delft3D-FLOW program, according to the procedure described by Veras et al. (2021). It is necessary setup data and some parameters for the area of interest, such as sea currents, temperature and salinity. Other data, such as the external contour conditions of the model, which include mean sea level and sea currents, were extracted from the global model TPXO (Egbert and Erofeeva (2023)), while the bathymetry data were obtained from the global model ETOPO (NOAA (2023)). The global models are elaborated in terms of astronomical components, where the observed tidal movement can be described as the synergy of a series of simple harmonic movements, each one having its own angular velocity (ω), amplitude A and the G phase. The general expression of the astronomical tide is (Deltares (2013)):

$$H(t) = A_0 + \sum_{i=1}^{k} A_i F_i \cos(\omega_i t + (V_0 + u)_i - G_i). \quad (1)$$

H(t) being the water level at the instant t, A_0 is the average water level, k number of relevant constituents, F_i nodal amplitude factor and $(V_0 + u)_i$ is the astronomical argument. With this information, the model solves the Navier-Stokes equations and the transport equations (Deltares (2013)), and determines the hydrodynamic pattern of tidal velocities in the area of interest for the historical series of one year, represented in Figure 2 and Figure 3, starting on 01/01/2021. Samples are generated at 10 minute intervals.

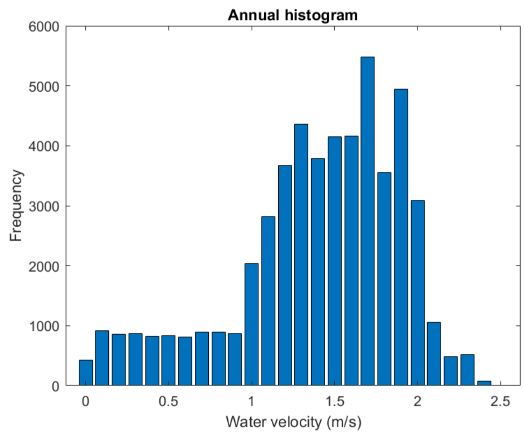

Figure 2. Frequency diagram of the tidal speeds of the Boqueirão Channel (year 2021).

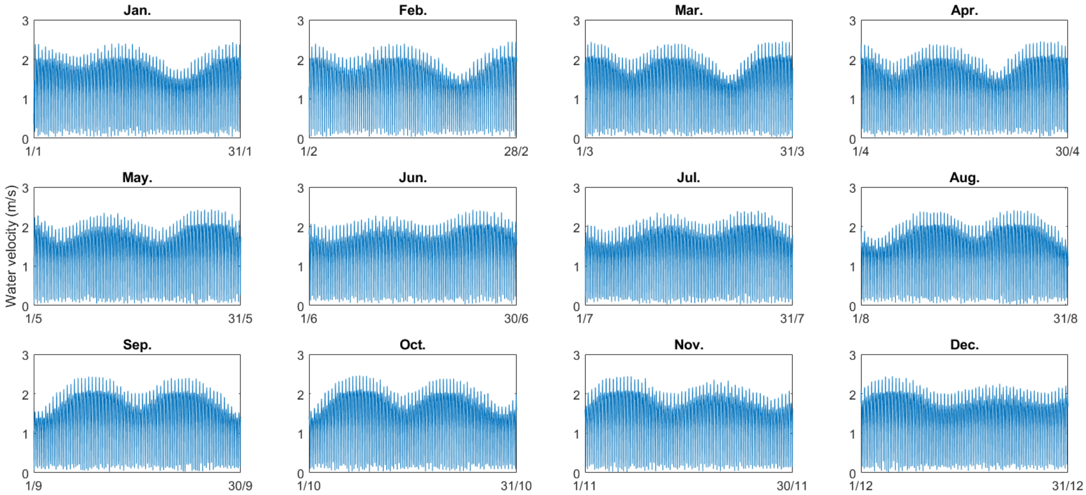

Figure 3. Temporal distribution of tidal speeds (year 2021).

The histogram in Figure 2 shows that the highest concentration of tidal velocities falls within the interval between 0.5 m/s and 2 m/s, representing about 82.57% of the total samples.

3. ASSESSMENT METHODOLOGY

3.1 Characterization of hydrokinetic turbines

Three configurations of the Tocardo T1 hydrokinetic turbine were chosen. To perform a performance comparison and determine their performance when subjected to the tidal conditions observed in the study area. The selection criteria were: tidal speed necessary for the turbine to work, since speeds below 2.5 m/s are observed in the Boqueirão Channel; and the size of each turbine. Technical information and power curves provided by the manufacturer are considered.

The Tocardo T1 hydrokinetic turbine, Figure 4, has power ranging from 40 to 100 kW, rotor diameter ranging from 3.1 to 6.3 m and different rated water velocitys, depending on the chosen configuration. Due to its size, it is ideal for community tidal energy projects, according to Hidrowing (2023).The technical specifications, for configurations A, B and C, are presented in Table 1. The generator output curves, for configurations A, B and C, are shown in Figure 5.

Figure 4. Hydrokinetic Turbine Tocardo T1.

Table 1. Technical specifications of the Tocardo T1 turbine - configurations A, B and C

Characteristics	A	B	C
Rated water velocity (m/s)	2,0	2,5	3,0
Blade D (m)	6,3	5,1	4,4
Rated grid power (kW)	42	55	66
V_{ci} (m/s)	0,4	0,5	0,6
V_{co} (m/s)	2,6	3,8	4,5
survival water speed (m/s)	4	5	6

Source: Hidrowing (2023)

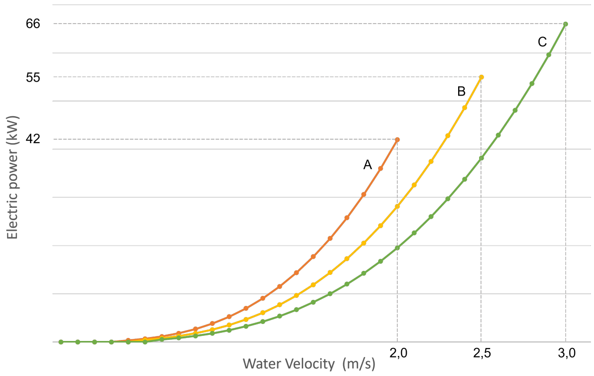

Figure 5. Output curve of the generator (P_e) - configurations A, B and C.

3.2 Performance evaluation

The performance evaluation of the hydrokinetic turbines was carried out following the approach adopted by Ramos et al. (2014). The electricity production (E_e) and the specific efficiency (η_{ss}), given by:

$$E_e = \int_0^T P_e(V,t)\,dt \tag{2}$$

and

$$\eta_{ss} = \frac{E_e}{E}. \tag{3}$$

Where P_e is the electrical power generated by the turbine, obtained through the curve provided by the manufacturer, which already takes into account the Betz limit.

The available power (P) in a mass of water passing through the turbine rotor and the available energy (E) during a period T (hours), are given by (Bahaj (2011)) :

$$P(t) = \frac{1}{2}\rho A V(t)^3. \tag{4}$$

and

$$E(t) = \int_0^T P(t)\, dt. \tag{5}$$

Where A is the turbine rotor area ($A = \pi R^2$), ρ is the fluid density in kg/m^3 and $V(t)$ the velocity of the tidal current at t.

The capacity factor (C_f) is given by the ratio between the production of electrical energy in a certain period of time T (in hours) and the energy that it would produce if it operated at nominal power Pr during that same time:

$$C_f = \frac{E_e}{TP_r}. \tag{6}$$

3.3 Physical guarantee

The amount of energy that a generation equipment can supply, given a defined criterion, is determined by the physical guarantee, EPE (2023). It is an important metric and, in Brazil, it is used to define the maximum amount of energy that a plant can commercialize in the National Interconnected System (SIN), in accordance with Brazilian Decree Nº 5.163/2004.

The Energy Research Company (EPE) is responsible for calculating the Physical Guarantee of generation projects, defined by specific regulations. In Brazil, there are no regulations that define a methodology for calculating the physical guarantee of ocean energy projects. However, given the similarity between both energy resources (wind and tidal currents), such an index may be an appropriate indicator to analyze the energy performance of a tidal current generation plant.

In this way, the methodology to determine the physical guarantee of wind projects was applied due to the similarity of the sources, given by:

$$GF = \frac{P_{90}.(1 - TEIF).(1 - IP) - \Delta P}{8760}. \tag{7}$$

Where P_{90} is annual energy production with incidence equal to or greater than 90% in MWh, TEIF is Equivalent Forced Outage Rate, IP is Scheduled Outage, ΔP is annual estimate of internal consumption and electrical losses up to the individual measuring point of the plant in MWh and 8760 is the number of hours in the year.

The EPE provides for a minimum value, equal to 2%, for the energy impact on wind farms due to forced stoppages (TEIF), EPE (2016).

4. RESULTS

4.1 Distribution of tidal current velocities

The annual distribution of tidal currents, figure 3, makes clear the occurrence of two spring tides throughout each month, when greater amplitudes and more intense currents are observed. It is possible to observe the occurrence of two neap tides per month, with smaller amplitudes and smoother currents.

Analyzing the distribution of tidal currents, Table 2 and Figure 6, noted that in all months the highest concentration is in the range from 0.5 m/s to 2 m/s (about 82%), so it is expected that a turbine operating in this range will perform satisfactorily.

Table 2. Distribution of speeds by interval (values expressed in %).

Month	Interval				
	0,5 a 2 m/s	1 a 2 m/s	1,3 a 2 m/s	1,5 a 2 m/s	≥ 2 m/s
Jan.	82,99	74,99	58,83	43,44	9,46
Feb.	82,42	74,06	57,52	41,38	9,99
Mar.	79,89	71,98	55,44	39,35	12,47
Apr.	81,1	72,997	56,7	41,35	11,65
May.	82,56	74,56	58,94	44,4	9,95
Jun.	83,9	75,78	60,64	46,37	9,03
Jul.	84,38	76,07	60,36	45,37	8,31
Aug.	83,19	74,74	57,48	40,31	9,24
Sep.	81,52	72,92	55,26	38,66	10,66
Oct.	82,36	73,57	56,25	39,39	10,16
Nov.	82,77	74,81	58,86	43,95	9,84
Dec.	83.73	75,71	60,79	46,4	9,21
Annual	82,57	74,35	58,1	42,54	9,996

Speeds lower than 0.5 m/s are observed at times of inversion of the direction of the water flow (moment of transition between high tide and low tide, or vice versa). São Marcos Bay has a semidiurnal tide, so there are two high tides and two low tides in the interval of approximately 24 hours.

It is possible to visualize that in the months of June and December the concentration of velocities between 1.5 m/s and 2 m/s is higher. The histogram in figure 6 shows that the month of March has a higher concentration of currents above 2 m/s when compared to the other months.

4.2 Hydrokinetic turbine performance evaluation

The turbines represented by the curves contained in Figure 5 were evaluated. The historical series of tidal speeds, Figure 3, was applied to the models of turbines A, B and C.

A performance comparison was performed and the Table 3 shows the annual electricity production (E_e), annual available energy (E), specific efficiency and capacity factor for the hydrokinetic turbines.

Turbine A presented a higher annual electricity production (177.45 MWh), as it has a larger rotor diameter and reaches rated power at a lower speed. The three turbines showed similar efficiency, ranging from 31.57% to 31.86%. Turbine A, presented a capacity factor equal to 48.38%, it is the only turbine (among those evaluated) that reaches

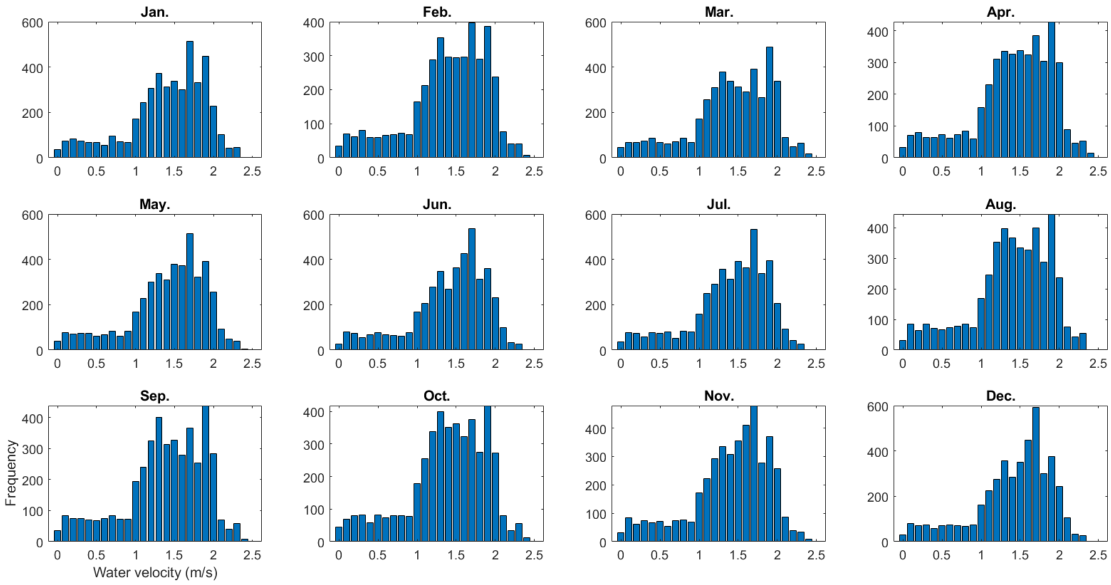

Figure 6. Monthly histogram of tidal speeds in the Boqueirão Channel (year 2021).

its maximum power when operating in the Boqueirão Channel, about 10% of the period operates at full power.

Table 3. Annual performance metrics - turbines A, B and C.

Metrics	A	B	C
E_e (MWh)	177,45	123,62	85,79
E (MWh)	557,03	390,22	271,71
η_{ss} (%)	31,86	31,68	31,57
C_f (%)	48,38	25,74	14,88

When subjected to a tidal speed of 2 m/s, the electrical power output is 42 kW, 28.16 kW and 19.55 kW for turbines A, B and C, respectively. Demonstrating that A provides greater electrical power, compared to the other turbines, when subjected to the same water speed. Turbine C, which has the highest Vci (0.6 m/s), operates in about 91% of the time series, the other turbines operate in an even longer period.

The performance metrics for each month, Table 4, were determined. Note the low fluctuation of the data over the months, due to the tidal profile. There is a variation between 13.55 MWh and 15.46 MWh for A, from 9.44 MWh to 10.87 MWh for B, and , from 6.55 MWh to 7.55 MWh for C. In 2021, the month with the lowest potential is February and the month with the highest potential for electricity production is March, as it has higher speeds. March is usually the month with the highest incidence of rain in the state of Maranhão, according to Cerqueira (2021).

The capacity factor ranges from 47.13% to 49.62% for A, from 25.12% to 26.66% for B and from 14.53% to 15.42% for C. The months with the highest capacity factor are March and April, as this is a factor related to the turbine's nominal power and this occurs at speeds above its Vr. March presents 12.47% of its tidal intensities greater than or equal to 2 m/s, therefore the turbines operate at a power closer to the nominal power.

The daily energy available and the daily energy produced is shown in Figure 7. The maximum energy (daily) produced by A is equal to 0.64 MWh, by B is equal to 0.47 MWh and by C is equal to 0.33 MWh. While the minimum energy produced was 0.21 MWh for A, 0.14 MWh for B and 0.098 MWh for C. The maximum production of the three turbines occurs on the same day, determined by the tidal profile and potentiated by the characteristics of the turbine.

Table 4. Monthly performance metrics (E_e in MWh and C_f in %).

	A		B		C	
Month	E_e	C_f	E_e	C_f	E_e	C_f
Jan.	15,18	48,72	10,56	25,89	7,33	14,98
Feb.	13,55	48,13	9,44	25,62	6,55	14,82
Mar.	15,46	49,62	10,87	26,66	7,55	15,42
Apr.	14,91	49,46	10,46	26,50	7,26	15,33
May.	15,22	48,85	10,59	25,95	7,35	15,01
Jun.	14,68	48,68	10,15	25,71	7,04	14,87
Jul.	14,96	48,03	10,35	25,37	7,18	14,67
Aug.	14,73	47,28	10,25	25,12	7,11	14,53
Sep.	14,28	47,38	10,00	25,33	6,94	14,65
Oct.	14,68	47,13	10,27	25,17	7,14	14,56
Nov.	14,57	48,33	10,13	25,66	7,03	14,84
Dec.	15,24	48,92	10,54	25,84	7,31	14,94
Annual	177,45	48,38	123,62	25,74	85,79	14,88

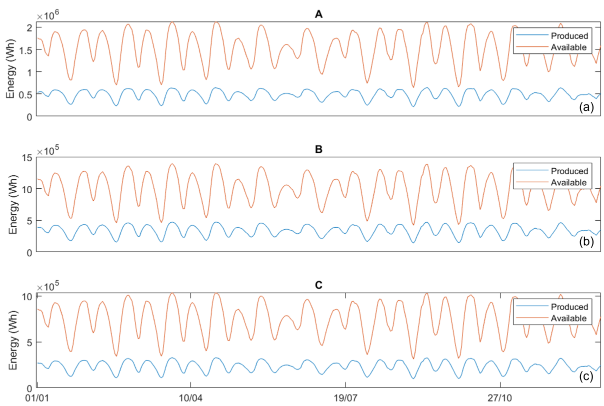

Figure 7. Daily available and produced energy: Tocardo (a) A (b) B and (c) C.

4.3 Physical guarantee

Figure 8 presents the permanence curve for (a) daily electrical energy and the respective (b) average speed, considering the Turbine A. The point P_{90} indicates the probability that approximately 90% of the energy equals or exceeds 341.85 kWh/day. The point P_{70} indicates the probability that 70% of the energy equals or exceeds 436.21 kWh/day. The average speed corresponding to P_{90} and P_{70} are 1.39 m/s and 1.52 m/s, respectively.

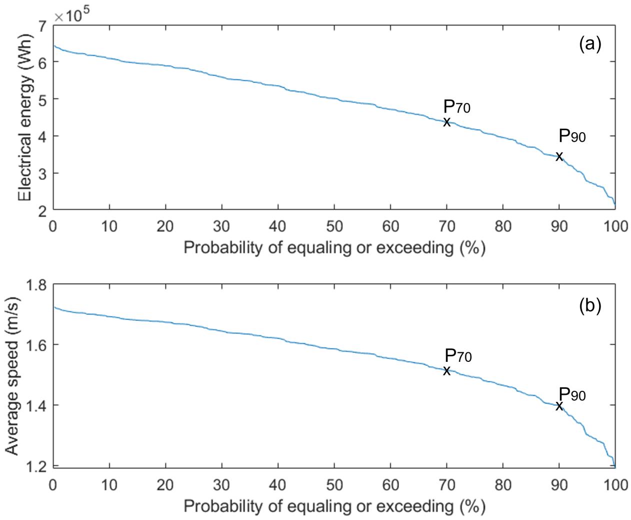

Figure 8. Permanence curve. (a) Probability of exceeding or equaling daily electrical energy. (b) Probability of exceeding or equaling mean tidal velocity.

The physical guarantee, used as a metric to define the maximum amount of energy that a plant can commercialize, Table 5, was verified taking into account annual energy production with an incidence equal to or greater than 90% (P_{90}) and 70% (P_{70}). Adopting TEIF, IP and ΔP equal to 2% each. Adopting the P_{70} means a physical guarantee 27.6% greater than that generated by the P_{90}, therefore, it impacts the amount that can be traded.

Table 5. Physical guarantee for turbine A.

	P_{70}	P_{90}
GF(kW)	17.092	13.39

5. CONCLUSION

The work presented the performance evaluation of three configurations of the Tocardo T1 hydrokinetic turbine, when applied to the tidal conditions of the Boqueirão Channel. Hydrokinetic turbines suitable for low and medium current speeds already exist on the market. The evaluated turbine, in general, present satisfactory performance, with remarkable electric energy production and efficiency.

Table 2 presents the frequencies of current velocities observed in the study site where velocities above 2 m/s were recorded. We could choose a turbine that has a nominal power equal to the highest observed speed and thus take advantage of the entire speed range of the site (for example, turbine B). However, the results show that this would not be a good idea, because most of the time we would be operating with the turbine in a region of low efficiency. This is associated with the non-linear shape of the generation curve, which grows with the cube of the velocity. When we choose turbine A (nominal speed of 2.0 m/s), 42.54% of the speeds are between 1.5 and 2.0 m/s, which corresponds to a range close to the turbine's nominal value. As a result, turbine A achieves the highest energy productivity for the site. It was the only one to reach its nominal power during the operation in the Boqueirão Channel. However, the rotor of turbine A has a slightly larger diameter, which eventually may require checking the effectively available area.

ACKNOWLEDGMENTS

The authors are grateful for the support of Federal University of Maranhão (UFMA), Federal Institute of Maranhão (IFMA), Foundation for Research and Scientific and Technological Development of Maranhão (FAPEMA), Coordination for the Improvement of Higher Education Personnel (CAPES) and the National Institute of Science and Technology in Ocean and Fluvial Energies (INEOF).

REFERENCES

Azevedo, T.N.A., El-Robrini, M., and Saavedra, O.R. (2022). "Assessment of Tidal Current Potential in the Pará River Estuary (Amazon Region–Brazil)". Available at SSRN 4113862.

Bahaj, A.S. (2011). "Generating electricity from the oceans". Renewable and Sustainable Energy Reviews, vol. 15, p. 3399-3416.

Cerqueira, H. (2021). “Avaliação Mensal de Chuva (março de 2021)”, [online]. URL: https://www.nugeo.uema.br/.

Czizeweski, A., Pimenta, F.M., and Saavedra, O.R. (2020). "Numerical modeling of Maranhão gulf tidal circulation and power density distribution". Ocean Dynamics. p. 1-16.

Deltares, D. (2013). “Delft3d-flow user manual”.

Egbert and Erofeeva (2023). “TPXO Global Tidal Models”, [online]. URL: https://www.tpxo.net/global.

Eletrobrás (1981). "Aproveitamentos Maremotrizes na Costa do Maranhão, Pará e Amapá. Inventário Preliminar".

EPE (2016). “Considerações sobre as taxas de indisponibilidade para cálculo e recálculo de Garantia Física de Projetos Eólicos”.

EPE (2023). “Garantia Física”, [online]. URL: https://www.epe.gov.br/pt/areas-de-atuacao/energia-eletrica/garantia-fisica.

Fouz, D., Carballo, R., López, I., and Iglesias, G. (2022). "Tidal stream energy potential in the Shannon Estuary". Renewable Energy, vol. 185, p. 61-74.

Gemaque, M.L., Vaz, J.R., and Saavedra, O.R. (2022). "Optimization of hydrokinetic swept blades". Sustainability, vol. 14.

González-Gorbeña, E., Rosman, P., and Qassim, R. (2015). "Assessment of the tidal current energy resource in São Marcos Bay, Brazil". Ocean Eng. Mar. Energy 1, p. 421-433.

Hidrowing (2023). “Tocardo T1”, [online]. URL: https://hydrowing.tech/turbines/tocardo-t1/.

NOAA (2023). “ETOPO Global Relief Model”, [online]. URL: https://www.ncei.noaa.gov/products/etopo-global-relief-model.

Oliveira, H.A., de Matos, J.G., de Souza Ribeiro, L.A., Saavedra, O.R., and Vaz, J.R.P. (2023). ”Assessment of Correction Methods Applied to BEMT for Predicting Performance of Horizontal-Axis Wind Turbines”. Sustainability, vol. 15.

Ortiz, G. and Kampel, M. (2011). ”Potencial de energia eólica offshore na margem do Brasil”. Instituto Nacional de Pesquisas Espaciais. V simpósio Brasileiro de Oceanografia.

Ramos, V., Carballo, R., Álvarez, M., Sánchez, M., and Iglesias, G. (2014). ”A port towards energy self-sufficiency using tidal stream power”. Energy, vol. 71, p. 432-444.

Rezek, T.J., Camacho, R.G.R., and Manzanares-Filho, N. (2022). ”A Novel Methodology for the Design of Diffuser-Augmented Hydrokinetic Rotors”. https://ssrn.com/abstract=4148357.

Veras, R.B.d.S., Costa, A.M.S., Cosme, D.L.S., Saavedra, O.R., Czizeweski, A.C., Torres Junior, A.R., and Pimenta, F.M. (2021). ”Modeling Tidal Streams of the Boqueirão Channel Using Delft3D”. TENCON 2021 - 2021 IEEE Region 10 Conference. p. 911-916.

Wen, Y. and Lin, P. (2022). ”Exploitation potential of tidal current energy in Southern China seas”. Energy Conversion and Management, vol. 267.

Yang, Z., Wang, T., Branch, R., Xiao, Z., and Deb, M. (2021). ”Tidal stream energy resource characterization in the Salish Sea”. Renewable Energy, vol. 172, p. 188-208.