# Modeling and Assessment of the Tidal Technical Potential in the Bacanga Estuary


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***Abstract*—Tidal generation from tidal gradients is one of the most technically mature ways to generate ocean electricity. This condition makes this model desirable for generating clean energy in several coastal regions worldwide. Among these regions, the Bacanga estuary, located in the urban region of São Luís, is historically considered an appropriate location for this generation model. Several studies have been conducted over the years to assess and demonstrate the energy potential of this location. However, a more detailed analysis regarding technical energy potential still requires further investigation. This study analyzes the Bacanga estuary's technical potential using bathymetric data, reservoir level restrictions, and a tidal turbine model. Different turbine configurations were evaluated in terms of diameter and number under different maximum reservoir levels to determine the energy sensitivity to variations in these levels. The results indicate that more giant diameter turbines are more sensitive to changes in the maximum reservoir level, and increasing this level from 2.0m to 2.5m could result in significant energy gains due to the local tidal profile. These findings suggest that adjustments to maximum reservoir levels could effectively increase energy production at tidal facilities.**



***Index Terms*—tidal power, renewable energies, energetic planning, technical potential, energy efficiency**


## I. INTRODUCTION

Historically, tidal power generation has not been widely adopted due to high installation costs and environmental concerns associated with constructing large dams [1]. However, recent technological advances, such as developing more efficient and less intrusive hydraulic turbines, have opened new perspectives on their economic and environmental viability [2], promising significant economic benefits in the future.

The first studies on the tidal energy potential in the Bacanga estuary date back to the 1980s, when a theoretical energy potential of around 160 GWh per year was estimated [3]. In 2012, through the project entitled *Research and Development for the Implementation of a Tidal Laboratory Plant in the Bacanga Estuary*, MCT/CNPq FNDCT Call for Proposals No. 05/2010, new campaigns were carried out to measure bathymetric and tidal data in the estuary. Based on these new data, a revised assessment of the estuary's theoretical energy potential was carried out, estimating a theoretical potential of around 145 GWh per year. More details of this study can be found in [4]. Later, in 2017, new studies were carried out proposing a conceptual model for the Bacanga tidal power plant, and preliminary studies were also carried out on the plant's technical energy potential, as published in [5]. During this period, several agents in the sector, including the Government of the State of Maranhão, have already expressed their support for implementing the Bacanga tidal power plant [6].

The studies above evaluated the theoretical potential (in [3] and [4]) and the technical potential for a specific turbine configuration (in [5]). However, given the operational restrictions due to the minimum and maximum limits of the estuary (as explained in the next section), it is appropriate to perform sensitivity analyses for different turbine configurations. This analysis allows us to assess the impact of choosing a specific configuration on the plant's energy generation. In addition, it can be helpful to evaluate the cost-benefit of other operating scenarios in which the current reservoir limits may eventually be extrapolated. For example, what would be the energy gain if it were possible to increase the maximum limit of the reservoir by 0.5 m? What should the turbine configuration (number and diameter) be that results in better energy production if the current restrictions of the estuary and the civil works existing at the dam are maintained? This article aims to contribute to the elucidation of these questions.

This study explores the Bacanga Estuary's technical potential for tidal power generation using a hypothetical double-regulated bulb turbine model designed explicitly for low-head studies. Unlike the study presented in [5], whose analysis of the technical potential focused on a single turbine configuration of the plant, the analysis proposed in this work addresses different turbine configurations, considering variations in diameter and number of units under different maximum reservoir levels. This method allows a detailed investigation of the energy sensitivity to variations in water levels, which is essential for optimizing the design and operation of tidal power plants.

The results of this research can contribute to developing energy solutions that combine technical efficiency and envi-


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ronmental sustainability by promoting renewable sources in coastal regions with characteristics similar to those of the Bacanga.

## II. Estuary Description

Located in the city of São Luís, Maranhão, the Bacanga estuary is considered a favorable location for strategic studies on the feasibility of exploring low-head hydro generation, such as tidal power plants. Fig. 1 shows an aerial view of the existing dam during low tide. Note on the left side of the image that the water level falls significantly during low tide, exposing the intake channel floors and stranding vessels near the dam.

Fig. 1. Aerial view of the Bacanga dam during low tide [4].

The average tidal variation is around 4.4 m, with its minimum and maximum values being 2.4 and 6.2 m, respectively (Fig. 2). Although these are significant tidal variations, generating electricity in this case becomes a challenge due to the very low head to which the electromechanical equipment must be subjected.

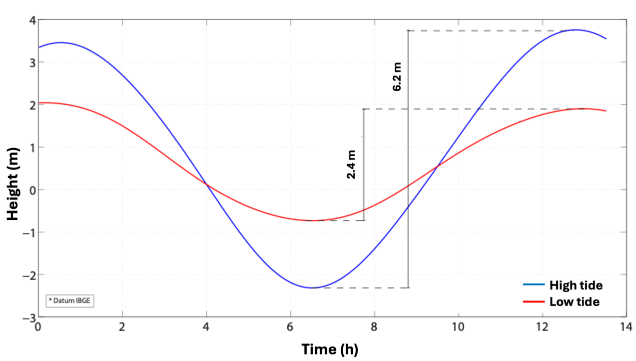


Fig. 2. Maximum and minimal tide variation in the estuary.

The Bacanga estuary, with its urban surroundings, is subject to a maximum high tide level of 4.0 m. However, the existing dam must be strategically operated, allowing the estuary to maintain a minimum and maximum water level of 0.0 m and 2.0 m, respectively. The minimum level is due to the need for a minimum amount of water in the reservoir for urban sanitation purposes, and the maximum level is to prevent flooding of urban occupations that have grown disorderly around the estuary over the last few decades. Consequently, this condition significantly reduces the reservoir's extractable potential, as the turbines must be operated at even lower heads. The maximum volume to be stored in the reservoir is estimated to be 13mi $m^3$ (the volume corresponding to the 2.0 m level) [5].

### A. Tidal Turbine

This study adopts a hypothetical model of a bulb-type tidal turbine with double regulation. This model was developed exclusively for research purposes by a commercial manufacturer of hydraulic turbines. The hill chart of this hypothetical turbine was initially presented for a research project described in [7] and has been used in several subsequent studies.

From the hill chart, the power generated and the flow through the turbine can be obtained from the following equations:

$$S_p = \frac{2 \times 60 \times f}{G_P} \tag{1}$$

$$n_{11} = \frac{s_p \times D}{\sqrt{H}} \tag{2}$$

$$Q_{11} = \begin{cases} 0.0166 n_{11} + 0.4861 & \text{if } n_{11} < 255 \\ 4.75 & \text{if } n_{11} \geq 255 \end{cases} \tag{3}$$

$$Q = Q_{11} \times D^2 \times \sqrt{H} \tag{4}$$

$$\eta_t = -0.0019 \times n_{11} + 1.2461 \tag{5}$$

$$P = \rho g H Q \eta_t \tag{6}$$

Where $S_p$ is the rotational speed of the turbine; $f$ is the electric frequency; $G_P$ and the number of generator poles; $n_{11}$ is the unit rotational speed; $D$ is the diameter of the turbine; $H$ he is the water drop available water; $Q_{11}$ is the unit flow rate; $\eta_t$ is the hydraulic efficiency of the turbine, efficiency of the turbine; $\rho$ is the density of the water; $g$ is the gravitational constant.

It's important to note that the hydraulic turbine hill chart is not specific to a single turbine model but rather to a family of models that share the same characteristics as long as they obey the abovementioned equations (affinity law). In this way, it becomes possible to evaluate the performance of turbines of different sizes, allowing for a sensitivity analysis. Furthermore, It is assumed that the turbine should operate at its maximum power output. Therefore, it is assumed that the blade angles and distributor controls are already implemented so that the turbine operates at the maximum power point.

### *B. Generation Model*

The generation model includes a series of harmonic constituents representing the sea level variation ($S_t$). Each harmonic constituent represents an astronomical phenomenon that composes the tides.

$$S_t = S_0 + \sum_{i=1}^{n} S_i cos\left(v_i + k_i\right) \quad (7)$$

where $S_0$ is the mean sea level, $S_i$ is the amplitude of harmonic component $i$, $v_i$ is the frequency of the astronomical phenomena associated with the harmonic component $i$, $k_i$ is the phase of the harmonic component $i$, and $n$ is the number of harmonic components included in the model. These additional data for the Bacanga estuary can be found in [8].

At each tidal cycle, the plant generation is evaluated according to the flowchart shown in Fig. 3. This flowchart is run recursively for sets of turbines of different quantities and sizes throughout the year.

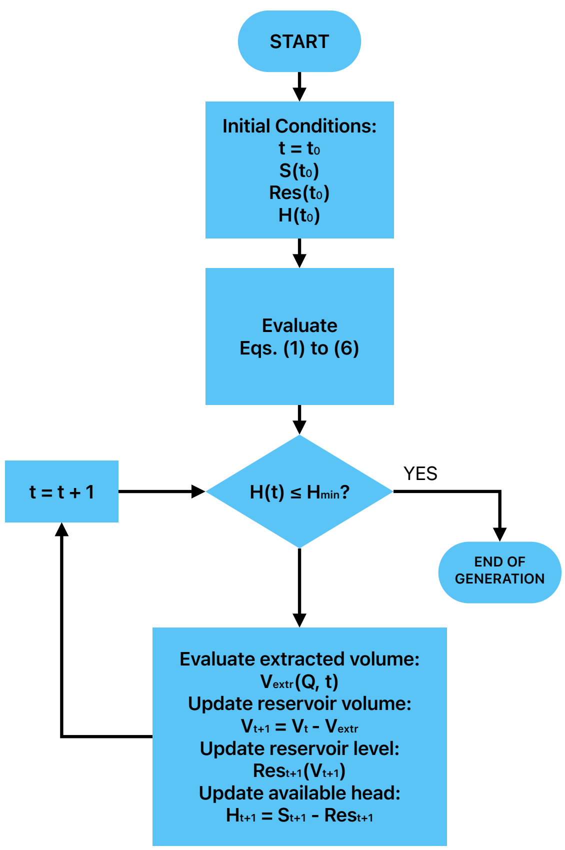


Fig. 3. Flowchart for the generation model at each tidal cycle.

## III. Results

This section presents results for three basic scenarios: Scenario 1, where only one turbine of different diameters is used; Scenario 2, which varies both the number of turbines and the rotor diameter (maintaining maximum variation of the reservoir at its actual value of 2.0 m) and Scenario 3, in which the maximum variation of the reservoir is expanded to 4.0m

### *A. Scenario 1 - One Turbine of different diameters*

Considering the initial scenario in which only one turbine is installed, Table I shows some operational indicators for different rotor diameters.

The turbine rotor diameter was set to vary between 1.5 m and 4.0 m, in 0.1 m increments. This condition results in wide variation in the plant's installed power (between 0.16 MW and 40.00 MW).

The annual energy produced varies significantly depending on the diameter of the turbine, with an inflection point when the diameter is equal to 3.8 m (maximum energy production). Turbines with larger diameters require larger heads to operate. For example, a turbine with a diameter of 3.8 m, coupled to a 50-pole generator, would need a minimum head of 2.2 m.

The peak generated power is proportional to the diameter of the rotor. However, larger turbine rotors require a higher minimum of water heads, so the generation time in each tidal cycle becomes shorter. This is also observed in the capacity factor: the higher the installed capacity, the lower the capacity factor. This indicates the underutilization of larger turbines and high variability in the power generated.

TABLE I
INDICATORS OF PLANT OPERATION AS A FUNCTION OF TURBINE ROTOR DIAMETER.

| Rotor Diameter (m) | Instaled Capacity (MW) | Generated Energy (MWh/yr) | Peak Power (MW) | Capacity Factor (%) |
|---|---|---|---|---|
| 1.5 | 0.16 | 595.35 | 0.13 | **41.29** |
| 1.6 | 0.23 | 786.56 | 0.18 | 39.50 |
| 1.7 | 0.31 | 1013.47 | 0.24 | 37.59 |
| 1.8 | 0.41 | 1274.10 | 0.32 | 35.51 |
| 1.9 | 0.54 | 1560.67 | 0.42 | 33.19 |
| 2 | 0.69 | 1858.72 | 0.54 | 30.59 |
| 2.1 | 0.89 | 2153.46 | 0.68 | 27.77 |
| 2.2 | 1.12 | 2435.85 | 0.86 | 24.89 |
| 2.3 | 1.40 | 2704.63 | 1.08 | 22.13 |
| 2.4 | 1.73 | 2971.00 | 1.29 | 19.65 |
| 2.5 | 2.12 | 3242.06 | 1.43 | 17.48 |
| 2.6 | 2.58 | 3516.54 | 1.58 | 15.59 |
| 2.7 | 3.11 | 3791.60 | 1.73 | 13.92 |
| 2.8 | 3.73 | 4064.12 | 1.89 | 12.44 |
| 2.9 | 4.45 | 4330.02 | 2.06 | 11.12 |
| 3 | 5.27 | 4584.34 | 2.23 | 9.93 |
| 3.1 | 6.21 | 4821.37 | 2.41 | 8.87 |
| 3.2 | 7.27 | 5035.21 | 2.60 | 7.90 |
| 3.3 | 8.48 | 5221.90 | 2.79 | 7.03 |
| 3.4 | 9.85 | 5377.79 | 2.99 | 6.23 |
| 3.5 | 11.39 | 5500.40 | 3.19 | 5.51 |
| 3.6 | 13.11 | 5588.17 | 3.40 | 4.87 |
| 3.7 | 15.03 | 5642.35 | 3.61 | 4.28 |
| 3.8 | 17.18 | **5662.91** | 3.81 | 3.76 |
| 3.9 | 19.56 | 5646.62 | 3.94 | 3.30 |
| 4 | 22.20 | 5584.66 | 4.07 | 2.87 |
| 4.1 | 25.11 | 5469.32 | 4.19 | 2.49 |
| 4.2 | 28.33 | 5283.40 | 4.32 | 2.13 |
| 4.3 | 31.87 | 5023.10 | 4.44 | 1.80 |
| 4.4 | 35.75 | 4664.53 | 4.56 | 1.49 |
| 4.5 | 40.00 | 4234.62 | **4.68** | 1.21 |

### *B. Scenario 2 - Multiple Turbines*

Fig. 4 shows the plant's installed capacity based on the combination of different rotor diameters and the number of turbines. The analysis contains a wide range of rotor diameter and turbine quantity, which results in an extensive range of installed capacity values. Observe that achieving a specific installed capacity value can be achieved through different turbine configurations. However, the annual generated energy can vary greatly among these configurations despite yielding the same installed capacity. This can be seen in Fig. 5, which shows the energy generated by the plant according to these different configurations.

As shown in Fig. 5, there is a high sensitivity relationship between the energy generated and the turbine configuration. As expected, when using fewer turbines, it's necessary to use a larger diameter to reach the same produced energy. Furthermore, this figure shows that the best turbine configuration consists of using several turbines of smaller diameters. Another finding is the possibility of achieving the same annual generation from different configurations. For example, one set of two turbines of 3.1 m diameter and a set of four turbines of a 2.2 m diameter will generate almost the same annual energy.

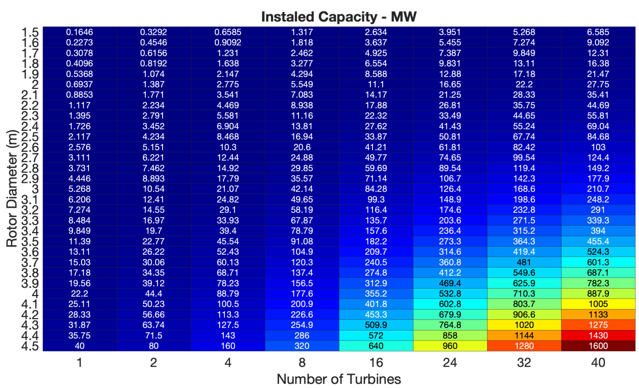


Fig. 4. Installed capacity from the combination of different values of rotor diameter and number of turbines.

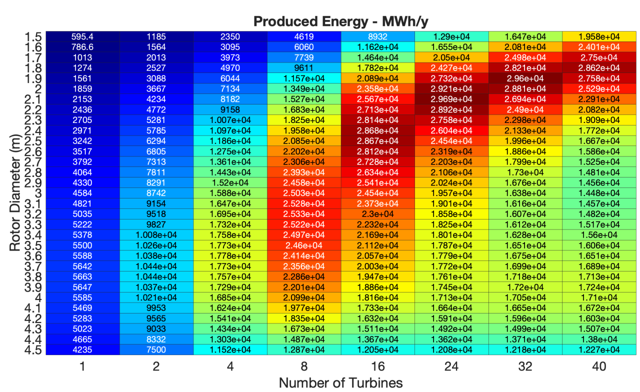


Fig. 5. Annual energy produced by the plant from different combinations of rotor diameter and number of turbines.

As we can see, energy performance should vary significantly according to the turbine configurations. This finding can also be seen in Fig. 6, which shows the energy generated by the plant, according to these different turbine configurations. It can be seen that there is a high sensitivity relationship between the energy generated and the choice of the plant's turbine configuration. The smaller the number of turbines, the larger the diameter needed to reach a peak of generated energy; however, after a specific optimum value, there is an inflection of this behavior. Furthermore, it is shown that the best turbine configuration consists of using several turbines of smaller diameters. Another observation is the possibility of reaching the same generation level with different turbine configurations. For example, consider a power generation value equal to 10,000 MWh/a. This produced energy can be achieved through two turbines of 3.3 m in diameter (totaling 16.97 MW of installed capacity) or four turbines of 2.3 m in diameter (totaling 5.58 MW of installed capacity).

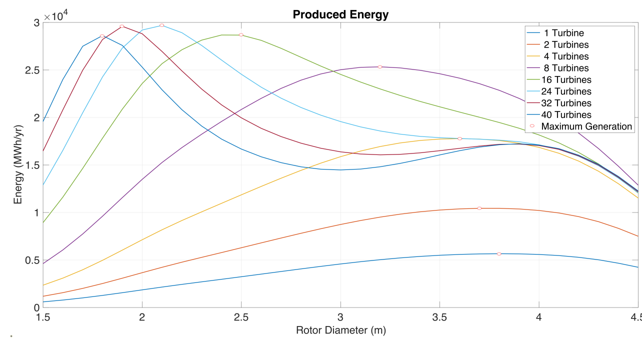


Fig. 6. Produced energy as a function of the quantity and diameter of the turbines.

### *C. Scenario 3 - Multiple Turbines + Variation in maximum level*

The previous section assessed the behavior of produced energy and installed capacity for different turbine configurations. However, all the previous analyses have the premise that the maximum level of the reservoir is the same and equal to 2.0 m (actual estimated value for the existing dam). However, how do these parameters behave if we alter the maximum level of the reservoir?

The energy generated varies significantly depending on the maximum reservoir level. Figs. 7 to 9 show the percentage variation of energy generated by the reservoir if maximum reservoir levels of 1.5 m, 2.5 m, and 4.0 m, respectively. Note that the percentage values are relative to the energy generated where the maximum level equals 2.0 m. Consider, for example, Fig. 7, in which a maximum reservoir level equal to 1.5 m would cause a reduction of up to 73.51% on the produced energy (set of 8 turbines with a diameter of 4.5 m).

Analyzing Figs. 7 to 9 together shows the following highlights:

- In general, some turbine configurations are more sensitive to variations in the maximum level of the reservoir. More specifically, this sensitivity increases as the diameter of the turbine increases, i.e. smaller turbines are more

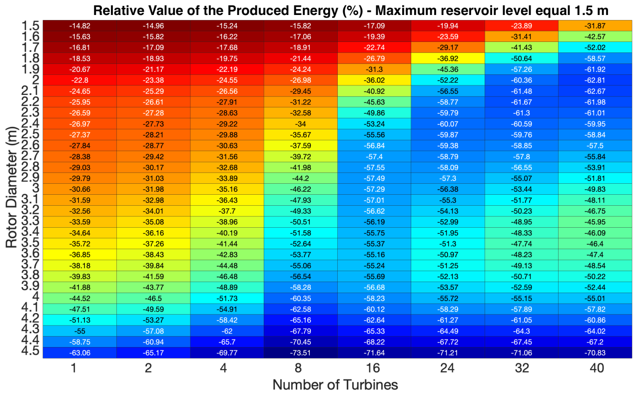


Fig. 7. Percentage variation in the energy generated if the maximum reservoir level is equal to 1.5 m.

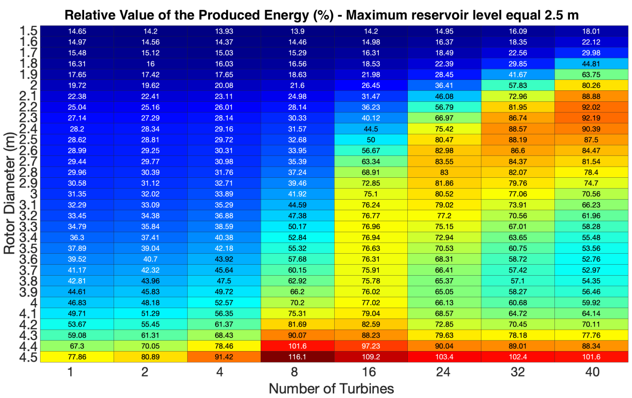


Fig. 8. Percentage variation in the energy generated if the maximum reservoir level is equal to 2.5 m.

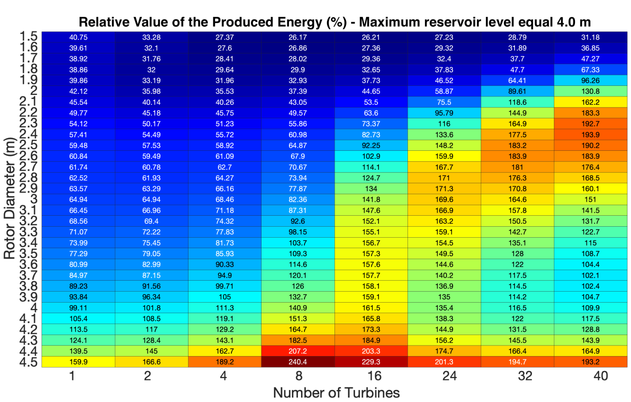


Fig. 9. Percentage variation in the energy generated if the maximum level of the reservoir is equal to 4.0 m.

suitable for the exploitation of the estuary in its actual condition; however, if we consider increasing the maximum level of the reservoir, larger turbines may provide a greater incremental gain in the produced energy;

- The greatest incremental gain in energy generated occurs when the maximum level of the reservoir is raised from 2.0 m to 2.5 m. This is due to the characteristics of the tides on the site, which even quadrature tides could fill the reservoir to its maximum level. This is an optimistic finding, as it indicates that any efforts to increase the maximum level of the reservoir can bring significant gains in the produced energy.

## IV. Conclusions

The study in the Bacanga Estuary analyzes the application of tidal turbines, considering specific variations in reservoir levels and turbine configuration. This analysis revealed that increases in the maximum level of the reservoir, especially from 2.0 m to 2.5 m, result in significant increases in the energy generated. Moreover, turbines with larger diameters are more sensitive to changes in the reservoir level, which suggests that the selection of turbines must be meticulously adapted to the bathymetric characteristics and tide variations. On the other hand, the maximization of the produced energy is observed not only by adjusting the reservoir level but also by the appropriate choice of the diameter of the turbines.

It is important to mention that this study performs a sensitivity analysis of the technical potential of the estuary, considering a wide range of variations in both the number and diameter of the turbines. The Bacanga estuary already has a dam, and the existing proposals would be to adapt this structure to produce electricity. The dam design is incompatible with installing many tidal turbines (structural restrictions of the dam and limitations of physical space). Thus, the total usage of the energy potential of the estuary is impracticable. Despite this, the relevance of this study lies in evaluating the most appropriate configuration of the plant, even in a minimal space of options both in terms of the number and the diameter of the turbines. In addition, the recovery, even if partial, of the maximum level of the reservoir, is an aspect discussed through municipal public policies, for example, through the urban evacuation of the flooded initial areas. The cost-benefit of this action would need to be carefully evaluated, and the gain in electricity production, as evaluated in this study, should be an item to be included in this policy.

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