PERSPECTIVE FOR ENERGY EXPLOITATION ALONG THE BRAZILIAN COAST

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The constant need to supply the growing global energy demand, leads to an increase in the generation of greenhouse gases. To circumvent this problem, more and more alternative means of energy generation have been used to compose the energy grid. One of the alternatives, which in recent decades has received great attention from researchers, is the conversion of wave energy into electrical energy. In Brazil, studies have also gained momentum, and the possibility of implementing wave energy converters on the Brazilian coast is increasingly recognized. With this in mind, the present work aims to determine the regions on the Brazilian coast that are most capable of being explored through wave energy. For this, a simulation of 37 years of the Brazilian sea state, is used in conjunction with a multicriterial methodology, where the logistical and energetic conditions of the Brazilian coast are quantified. Subsequently, power matrices of 8 wave converters are used to quantify the theoretical potential generated in the improved locations. The results showed that, in energy terms, the South and Southeast regions of Brazil have the greatest potential. This factor also proved to be the cause of the presence of lower logistical indexes in these regions, when comparing them with the North and Northeast regions of Brazil. After parameterization of the indices, three zones of interest were observed on the Brazilian coast: Cabo Frio, Imbituba and São José do Norte. When applying the conversion matrices in these locations, average daily generation power between 1.5 and 230 kW were observed, the largest being located in the Cabo Frio region, using the BHBA model of converter. Variability in energy production was also discussed, and it should be a primary factor in the choice of the convert model, as well as in its design. Finally, all results were consistent with previous work, however, the path to implementing a wave energy conversion site in Brazil is still long, and should be focused on optimizing devices for Brazilian waters.

INTRODUCTION

Due to the world energetic crisis, more and more, governments are willing to expand their renewable sources to diminish the oil and gas dependency. Many countries already have a great renewable infrastructure, mostly based on wind and solar power. Although, the development of different technologies to expand range of inputs at the energetic matrix is essential to reduce possible power shortages.

Wave energy, even though isn't a new concept (Shaw, 1982), has become a constant research topic in the last decade, mostly, due to the computational advances and prototype testing. At global level, several researches identifying the wave potential have been made (Cornett, 2008; Reguero et al., 2015). The same, applies for smaller regions where it's important to better describe local characteristics and wave variability (Pianca et al., 2010; Espindola and Maurı, 2017; Guimarães et al., 2019).

However, the quantification of available theorical wave potential is only the first step to enable the energy exploitation. Transmission costs, the logistics involved in operation, maintenance and deployment, the converters technology which will be used, all these factors are essential for a viable implementation. Weiss et al 2018, for example, presented and study where all these points were taken into account, and based on a set of indexes, zones of interest, for wave and wind exploitation, were determined around the globe.

Brazil has a large offshore area which could potentially be used for various forms of renewable energy generation. To exploit those areas, though, all the factors mentioned before must be assessed. The wave conditions must be well identified, ports and electrical infrastructures mapped, inter and intra annual variability studied, and so on.

The aim of the present work is, based on Weiss et al. (2018) multicriteria method, with adaptations to the Brazilian climate, determine wave exploitation hotspots at the coast. To accomplish that, firstly a wave climate hindcast was produced using Tomawac wave model. With the results of the hindcast, it was them possible to use a set of multicriterial indexes along the coast and finally identify zones of interest for the deployment of wave energy converters (WEC's).

MATERIALS AND METHODS

To enable the evaluation of the multicriteria method, a hindcast of the Brazilian ocean wave climate was produced. Using Guimarães et al. (2019) model, the results were extended, obtaining 37 years, from

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1979 to 2016, of sea state. Figure 1 shows the mesh used with TOMAWAC generation and propagation model. The unstructured mesh has a variable density, with node distance varying from $50\,\text{km}$ near the oceanic boundary to less than $300\,\text{m}$ at some nearshore areas. TOMAWAC model solves the wave action equation which outputs the parameters of interest, significant wave height (H_s), peak period (T_p) and mean direction (D_m) for the application of the multicriteria method.
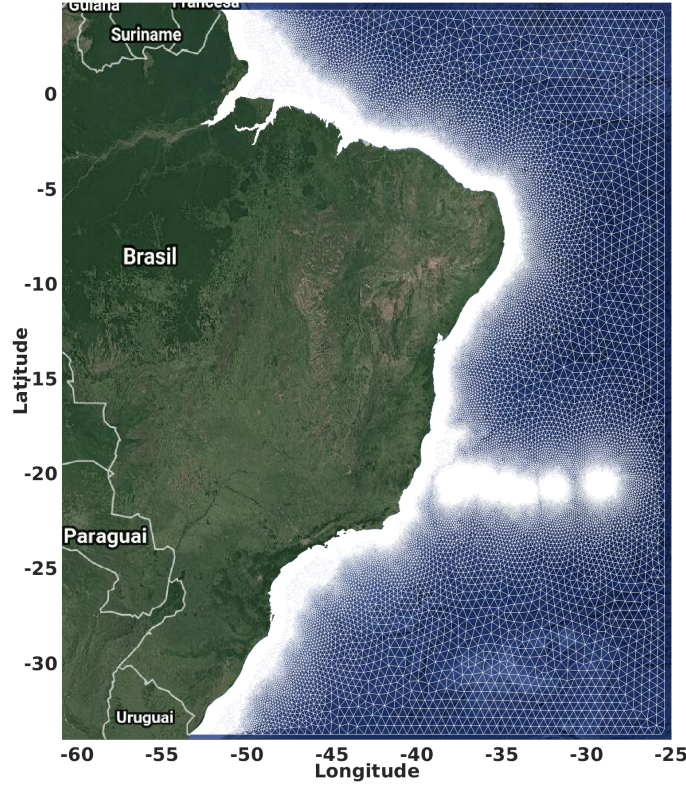

Figure 1: Computational mesh used in the simulation. Source of terrain image: Google Maps.

The method, based on Weiss et al. (2018), consists in evaluating multiple indexes, that account for the logistics and the wave energy of the locations. After that, a potential zone index is determined, revealing the zones of interest for the exploitation of wave energy at the Brazilian coast.

Logistic Indexes

The logistic indexes are expected to evaluate, transport, maintenance and energy transmission. Essential factors for a viable WEC farm. The harbour index ($I_{Harbour}$) evaluates the distance between the nodes of the mesh and the nearest port. 31 coastal ports in Brazil were considered, even though some of them might not be able, at the moment, to handle this type of operation. The follow parametrization function determines, in an index from 0 to 1, how close each node of the mesh is to a port:

$$
I_{Harbour}(\dot{x}) = \begin{cases} \frac{-0.8}{250}\dot{x} + 1 & \text{for } \dot{x} \leq 250 \\[2ex] \frac{0.2(\dot{x}-4.92e+03)}{250-4.92e+03} & \text{for } \dot{x} > 250 \end{cases}
\tag{1}
$$

The consumer centre index (I_{CC}) is also based on a parametrization function. This time, the I_{CC} intends to expose nodes closer to coastal consumer centres. For that, all coastal cities with over 200 thousand habitants were considered ((IBGE, 2010, 2011)). The aim for cities with this population size, is to assure the electrical distribution capabilities of the region.

$$I_{cc}(\dot{x}) = \begin{cases} \frac{-0.8}{250}\dot{x} + 1 & \text{for } \dot{x} \leq 250 \\ \\ \frac{0.2(\dot{x}-5.48e+03)}{250-5.48e+03} & \text{for } \dot{x} > 250 \end{cases} \tag{2}$$

I_{LogHs} and I_{LogW} have a different approach. Using the wind and H_s time series for each node, it calculates the amount of timesteps in which the wind and H_s are under a security threshold for logistics operation.

$$I_{LogHs} = \frac{t_{over}}{t_{series}} \tag{3}$$

$$t_{over} = \begin{cases} 1 & \text{for } H_s \leq 2 \\ \\ 0 & \text{for } H_s > 2 \end{cases} \tag{4}$$

$$I_{LogW} = \frac{t_{over}}{t_{series}} \tag{5}$$

$$t_{over} = \begin{cases} 1 & \text{for } W \leq 10 \\ \\ 0 & \text{for } W > 10 \end{cases} \tag{6}$$

Lastly, the main logistic index (I_{Log}) is evaluated. The iLog aims to expose the highest bottleneck for logistics operations at each node. And will be later used to determine the potential zone index:

$$I_{Log} = min(I_{Harbour}, I_{LogHs}, I_{LogW}) \tag{7}$$

Energetic Indexes

The energetic indexes aim to characterize the conversion potential each node has. For that, the power index (I_{Pw}) computes the amount of timesteps in each node that the H_s and T_p are under wave energy generation limits:

$$I_{Pw} = \frac{t_{over}}{t_{series}} \tag{8}$$

$$t_{over} = \begin{cases} 1 & \text{for } 2 \leq H_s \leq 7.5 \ \& \ 5 \leq T_p \leq 16 \\ \\ 0 & \text{for other values of } H_s \text{ e } T_p \end{cases} \tag{9}$$

The adopted limits were based on Weiss et al. (2018) method and Babarit et al. (2012) et al power matrix approach.

The other energetic index, survival index (I_s), computes based on an parametrization and the Hs time series, the amount of time the wave condition will preclude the WEC's to operate due to storm conditions:

$$I_s^t(\dot{x}) = \begin{cases} \frac{-0.8}{15}\dot{x} + 1 & \text{for } \dot{x} \leq 15 \\ \\ \frac{0.2(\dot{x}-16.88)}{15-16.88} & \text{for } \dot{x} > 15 \end{cases} \tag{10}$$

Potential Zone Index

To bring together all the indexes, the potential zone index (I_{PZ}) takes into account the minimum and the maximum values of every index at every node. This way, the nodes with the highest I_{PZ} represent the zones which the exploration of wave energy is recommended:

$$I_{PZ} = \frac{min(I_{Log}, I_{cc}, I_{Pw}, I_s)}{max} * 100 \tag{11}$$

Extraction Potential

To evaluate the extraction potential of the sites, the top 3 I_{PZ} locations where selected for a better understanding of the generation capabilities. Using H_s, and T_p timeseries of these sites, the theoretical energy output was assessed using Babarit et al. (2012) power matrixes. 8 models, presented in table 1 were used, each with its own properties simulated. The evaluation at each time step was then analysed in terms of annual means, providing a better look trough the intra-annual variability.

Table 1: Conversores utilizados para o cálculo do potencial teórico de energia das ondas. Fonte dos dados: Babarit et al. (2012)

Name	Acronym	Operation depth (m)	Prototype
Small bottom-referenced Heaving Buoy	Bref-HB	40 to 100	Seabased WEC[1]
Bottom-referenced Submerged Heavy-Buoy	Bref-SHB	20	CETO WEC [2]
Floating two-body Heaving Converter	F-2HB	Deep Water	Wavebob (Weber et al., 2009)
Bottom-fixed Heavy-Buoy Array	B-HBA	13	Wavestar WEC [3]
Floating Heave-Buoy Array	F-HBA	Deep Water	Pontoom Power Coverter [4]
Bottom-fixed Oscillating Flap	B-OF	13	Oyster WEC (Cameron et al., 2010)
Floating three-body Oscillating Flap Device	F-3OF	Deep Water	Langlee WEC (Pecher et al., 2010)
Floating Oscillating Water Column	F-OWC	Deep Water	OE Buoy [5]

[1] `https://www.seabased.com`
[2] `https://www.carnegiece.com/technology/`
[3] `http://wavestarenergy.com`
[4] `https://www.pontoon.no`
[5] `https://oceanenergy.ie/oe-buoy/`

RESULTS

Brazil large costal area presents a rather variable wave climate. Guimarães et al. (2019) shows that the south region has the highest available potential reaching almost 20 kW/m, 15 to 20 km from the coast [Fig. 2]. Areas closer to the coast have lower potential for energy production, but the shorter distance from the coast has a high impact on the logistical indexes. Finding the balance between available wave energy and practical distances for deployment and maintenance is key for higher Potential Zone Index.
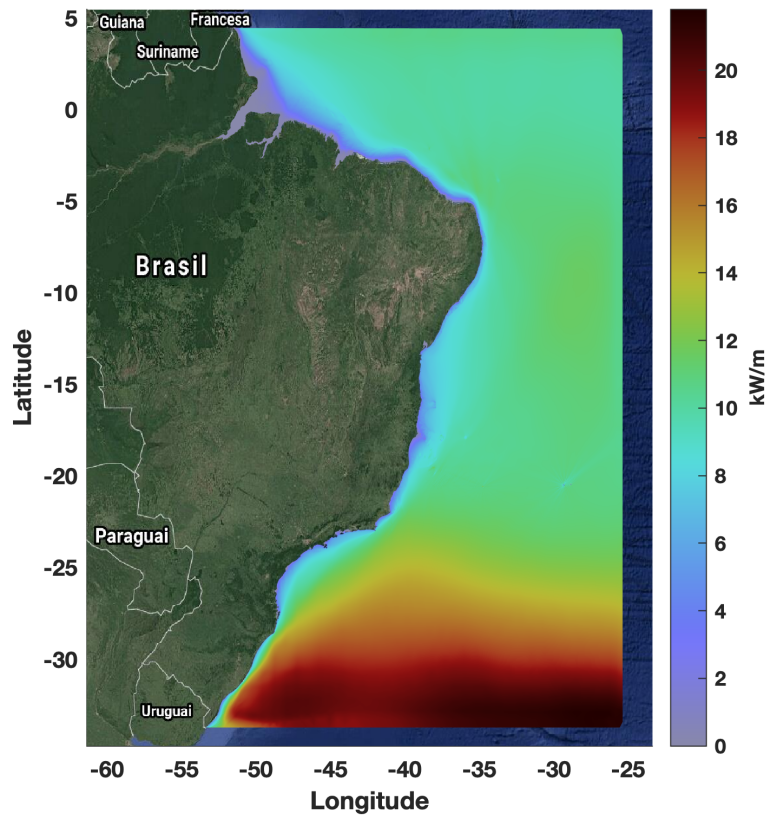

Figure 2: Mean surface wave potential of the Brazilian coast. Source of terrain image: Google Maps.

Nevertheless, the I_{CC} [Fig. 3] and I_{Log} presented elevated values along most of the coast. This is explained by the fact that large consumer centres are in coastal regions, thus providing grid and ports infrastructure. The regions with the lowest indexes are situated in South Region, but this happens due to more frequent intense winds and higher waves, which will cause greater challenges for deployment and maintenance.
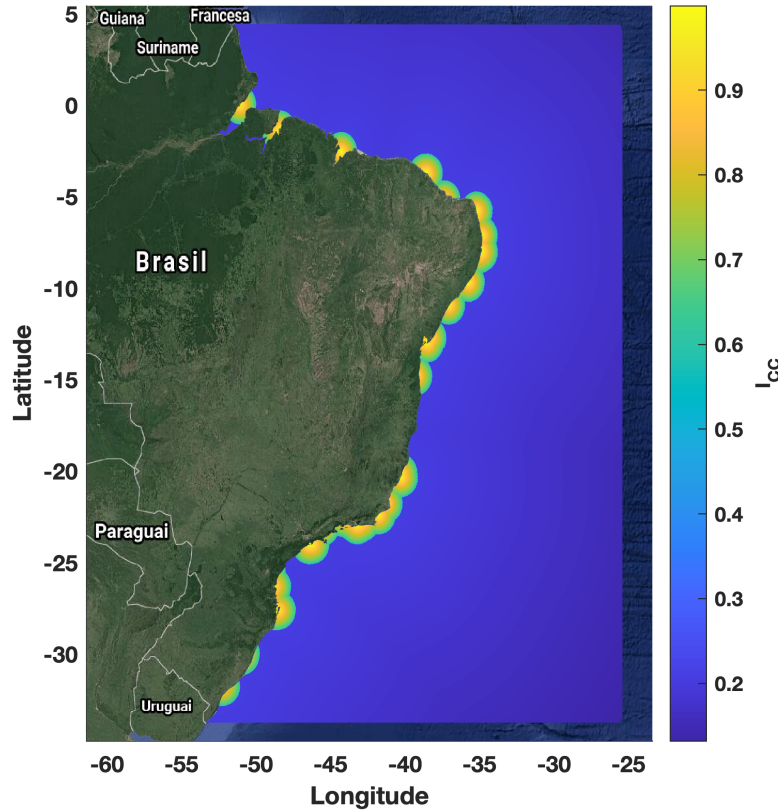

Figure 3: I_{CC} **distribution at the Brazilian coast. Source of terrain image: Google Maps.**

The I_s shows a similar pattern close to the coast, mostly, due to the fact that the high wave energy areas are further away from the shoreline. Even so, the north and northeast regions presented higher average indexes than most of the south and southeast coastal cities. However, the higher I_s up north is also associated with and lower I_{Pw} at those regions. This time, the higher wave potential at the south regions evidences the better results. Although, due to the parametrization used, the values presented are extremely low all over the coast, being the highest, 0.293 in Cabo Frio (RJ). This is explained by the fact that, both, Weiss parametrization and Babarit power matrix were designed with other regions in mind. With the IPZ computed, three areas stood out: São José do Norte (Rio Grande do Sul), Imbituba (Santa Catarina) and Cabo Frio (Rio de Janeiro) [Fig. 4], all cities found at the South or Southeast regions of Brazil. These areas showed the highest I_{PZ} values in Brazil, and were the selected sites to evaluate the output energy provided by the set of WEC's

Two other locations presented results worth of further investigation: the Northeast Region (RN, PB, PE), and some areas at the São Paulo State (Table 1), mostly with some optimization of the indexes criteria.

Extracting H_s and T_p time series at the three previously define hotspots, it was possible to access the amount of theoretical energy produced by distinct types of WEC's in these locations. Some limitations were visible in São José do Norte and Imbituba, the depth or these regions forbids some of the WEC's to run due their physical characteristics. In Cabo Frio, all 8 WEC's were used to compute the power output.
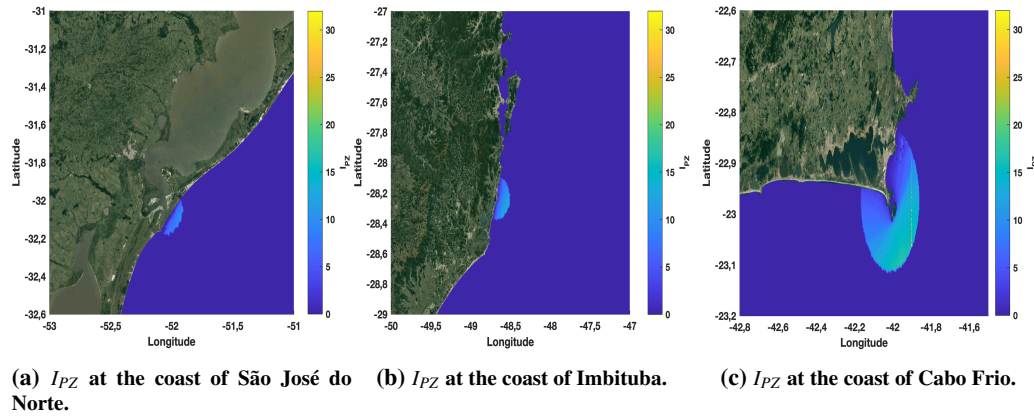
(a) I_{PZ} at the coast of São José do Norte.   **(b)** I_{PZ} at the coast of Imbituba.   **(c)** I_{PZ} at the coast of Cabo Frio.

Figure 4: Highest I_{PZ} locations at the Brazilian coast.

Table 2: Indexes for selected spots at the Brazilian coast.

City	I_{CC}	I_{Log}	I_s	I_{Pw}	I_{PZ}
Cabo Frio - RJ	0.754	0.853	0.916	0.293	31.996
Ilhabela - SP	0.712	0.950	0.945	0.034	3.632
Imbituba - SC	0.764	0.876	0.919	0.123	13.462
Salvador - BA	0.969	0.974	0.935	0.025	2.569
São José do Norte - RS	0.827	0.901	0.932	0.09	10.605

Comparing the sites, Cabo Frio presented, as expected, the highest energy output, almost double what can be produced in São José do Norte, an about 10 % more than in Imbituba. The greatest WEC at Cabo Frio, outputted a daily mean of 230.57 kW, while the same equipment delivered 126.60 kW in São José do Norte and 204.65 kW in Imbituba.

Another key factor is the consistence that this energy is delivered. São José do Norte presented the highest variability between the sites, bringing a crucial point for discussion. Is a consistent lower output site better at long term than a high output and highly variable site? Further investigation must be done to correctly answer the appointment.

Figure 5 presents the output for the set of 8 WEC's in a mean year, calculated taking the mean of every day for the 37 years of simulation.

Although spikes are present during the annual mean, the most visible discrepancy can be seen in February, when the lowest energy output is visible. Nevertheless, Cabo Frio present a quite stable energy output during the entire year, without great seasonality, which must be said, is greater with the highest output WEC's.

CONCLUSIONS

Using an adaptation of the methodology proposed by Weiss et al. (2018), it was possible to assess the wave energy exploitation potential of the Brazilian coast. The index analysis showed that in logistics terms, almost all the Brazilian coastline is well served with ports and city infrastructure. The energy indexes, on the other way, make explicit the observed difference of the theoretical wave power of the southern areas of Brazil against the northern. The potential zone index pointed 3 zones that stood out. Cabo Frio, Imbituba and São José do Norte, are cities worth more in-depth research.

The main improvement points, come from a better adaptation of the parametrization, mainly, the ones that assess the energy. With a different climate, Brazil showed that the thresholds used by Weiss et al. (2018) must be reassessed, in order to produce results that do not cause insecurity due to low I_{Pw}. This methodology also proves to be convenient for the assessment of vulnerability and risk to climate changes, as one can forecast future wave climate, and decide where and how to implement offshore energy generating devices, considering future XXI wave climate scenarios (Amores 2020; Jiang 2020).
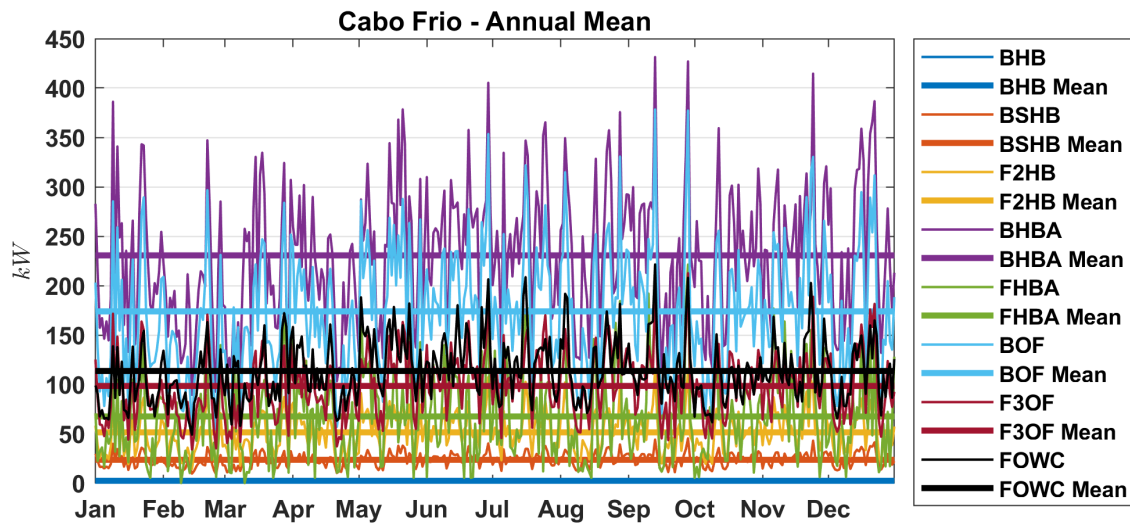
Figure 5: Energy output annual mean at Cabo Frio site.

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