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On the wave energy potential along the southern coast of Brazil

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Abstract
The ocean wave energy resource is a real alternative to supply part of the energy demand in various countries, since some locations have a remarkable capacity to generate electricity. The objective of this study is to evaluate the energy resource of ocean waves in the coast of Rio Grande do Sul, the southern state of Brazil. This note presents the first results. The wave data used were collected in the sea area near the Port of Rio Grande during the years 1996 to 1999, amounting to sixteen months of monitoring. The data set was treated and grouped resulting information monthly, seasonal and annual basis. The annual average was found to be 8.6 kW per meter of wave front, reaching 14.0 kW per meter for the month of May and 4.0 kW per meter for the month of January. The results indicate good perspectives in obtaining power supplies.
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Keywords: Ocean energy; Ocean wave energy; Survey of energetic potential; Southern coast of Brazil.

1. Introduction

The generation systems based on renewable energy resources face several difficulties, due mainly to the high initial investments and low efficiency. Among the resources available, the energy of ocean waves provides a reasonable economic performance, achieving in several projects specific costs per installed power a little higher than the costs of wind farms.
One of the difficulties of generating energy from ocean waves is the high investment cost per kW installed, due to a lack of maturity of available solutions. However, even before they reach their economic maturity, it can be adopted in locations where feasible.
The expansion of renewable energy can contribute to the diversification of energy supplies, encourage new businesses, create jobs and contribute to the development of disadvantaged regions, offering several environmental advantages when compared to traditional sources of power generation.
In this scenario, it can be possible to consider that the plants that generate energy from ocean waves can contribute in meeting the energy needs causing little environmental impact, pollution-free air and with competitive costs of implementation and operation [1].
Generating energy from ocean waves can have great impact on the Brazilian energy grid, since Brazil has a vast coastline, with more than 9,000 km long, with a potential estimated at just over 30 GW in its southern and southeastern parts [2].
This paper presents a preliminary assessment of the potential to generate energy from ocean waves along the coast of Rio Grande do Sul, the southernmost state of Brazil, based on a series of data obtained with a wave rider buoy, as described by the following chapters.

The project will continue with the installation of buoys at various locations along the study area, to obtain longer series of data.

2. Energy from ocean waves

The objects on the surface of the Earth have different heat capacities, which makes it warm or cool in different ways depending whether or not being irradiated by the Sun. Areas of high and low pressures are formed as the air moves over warm or cooled areas in different ways. As the winds acting on the ocean surface, they transfer their energy and cause the appearance of waves.

The mechanisms of energy transfer from wind to waves are complex. The air flowing over the sea surface transfers energy through the action of shear stresses, resulting in the formation and growth of waves. The turbulent airflow near the surface generates an intense variation of shear stresses and pressures. When such oscillations get in phase with the waves, there is an increase in the generation of waves [3].

The amount of energy transferred and the height of wind generated waves depend not only on wind speed, but the size of the area where it operates. In each of these steps, there is concentration of energy so that solar power levels on the order of 100 W/m2 can eventually turn into waves with power levels up to 1,000 W per meter of wavelength [4].

The ocean waves can be classified by various criteria, according to the period or frequency, with the disturbing forces and restoring forces. The shortest waves have the wind as the primary disruptive force, which acts at the interface between atmosphere and ocean. The longest waves have major storms and tsunamis as disturbing forces, as well as the motion of the Earth in orbit around the Sun and the Moon's motion in orbit around Earth. The Coriolis force acts as primary restoring force.

In a conservative dynamic system subjected to small amplitude oscillations, the kinetic energy and potential energy are equal. The average density of kinetic energy can be obtained by calculating the kinetic energy of a fluid element of height dz, length dx and unitary width, integrating between the surface and bottom, as it appears in Eq. (1). In this equation, Ec is the average kinetic energy density, u and v are the horizontal and vertical components of water particle velocity, dz is the height of the fluid element, dx is the length of fluid element, η is the surface elevation, ρ is the density of water, λ is the wavelength.

$$E_c = \frac{1}{\lambda}\int_0^{\lambda} dx \int_{-h}^{\eta} \frac{1}{2}\rho\left(u^2 + v^2\right)dz \tag{1}$$

Substituting the expressions for the components u and v, shown in Eq. (2), the average density of kinetic energy is obtained.

$$\begin{aligned} u &= a\omega \exp kz \cos(kx - \omega t) \\ v &= a\omega \exp kz \sin(kx - \omega t) \end{aligned} \tag{2}$$

In Eq. (2), a is wave amplitude, ω is the angular frequency, k is the wave number and t is time.

The average density of kinetic energy is shown in Eq. (3). The average density of potential energy, Ep, in the mean level (z = 0) is given by Eq. (4).

$$E_c = \frac{1}{4}\rho g a^2 \tag{3}$$

$$E_p = \frac{1}{4}\rho g a^2 \tag{4}$$

The average density of total energy, ET, is then given by Eq. (5).

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$$E_T = E_c + E_p = \frac{1}{2}\rho g a^2 \tag{5}$$

The average flow of energy is the rate at which wave energy propagates per unit length of wave crest, through a vertical plane perpendicular to the direction of wave propagation. It is obtained from the Cg group velocity and density of total energy ET by Eq. (6).

$$P = ETC_g \tag{6}$$

The velocity of propagation of wave energy is given by Eq. (7), where Cg is the velocity of propagation of wave energy. Thus, one arrives at Eq. (8) and the average power flow P is calculated for monochromatic waves through the simple Eq. (9).

$$C_g = \frac{gT}{4\pi} \tag{7}$$

$$P = \frac{1}{2}\rho g a^2 . \frac{gT}{4\pi} \tag{8}$$

$$P = \frac{1}{32\pi}\rho g^2 H^2 T \tag{9}$$

The sea can be modeled as a random process, resulting from the superposition of a large number of monochromatic components. Thus, wave parameters such as time, height and direction should be treated by statistical methods. The statistical parameters used are the most significant height Hs and the average energy period Te.
The flow of energy for a real sea is calculated by Eq. (10), where ρ is the density of seawater, equal to 1025 kg/m3, g is the local gravity, S (f,θ) is the distribution of energy density in terms of frequency and direction.

$$P = \frac{\rho g^2}{4\pi} \int_0^{2\pi} \int_0^{\infty} S(f,\theta) f^{-1} df d\theta \tag{10}$$

Integrating Eq. (10) it could be obtained the power per length of wave front, Eq. (11), where P is the power in W/m.

$$P\ [W/m] = \frac{\rho g^2}{64\pi} H_S{}^2 T_e \tag{11}$$

Since (ρg2/64л) equals 490.60, the power could be expressed by Eq. (12).

$$P\ [kW/m] = 0.4906 H_S{}^2 T_e \tag{12}$$

To assess the energy resource, the average energy period, Te, was considered. The energy period was obtained from the average of zero crossing intervals considered for data collection. The final expression appears in Eq. (13).

$$T_e = 1{,}21 T_z \tag{13}$$

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This equation was used in this study to evaluate the energy resource from the data obtained in situ. It is equal to the equation presented by Twidell and Weir [5] and the discussion presented by Bahaj [6]. A more accurate determination requires a better knowledge of the statistical distributions of these quantities [7], obtained with longer series of measurements and with measurements at other locations along the coast.

3. Evaluating the energy resource

To evaluate the wave energy resource is necessary to obtain data on height and period of ocean waves. These data can be obtained with in situ measurements, remote measurements or numerical modeling.

The in situ measurements are generally made by wave rider buoys or submerged systems, such as acoustic sensors and pressure sensors. These methods is difficult to perform, there are risks of destruction or damage of equipment.

In this work, in situ measurements obtained with a wave rider buoy were used. Data acquisition was initiated in January 1996 and closed in December 1998. During the data acquisition two accidents occurred. Therefore, the gaps of the time series were filled.

The equipment used for data collection was a Directional Wave Rider buoy. This equipment consists of a buoy 0.9 m in diameter, fitted with accelerometers that measure accurately, in three directions, the accelerations experienced by the buoy because of the movement on the waves.

The buoy was programmed to collect data at intervals of three hours to significant heights less than 2 meters. In the case of storms, the acquisition was nearly continuous 30-minute interval between acquisitions.

In October 1996, the buoy was positioned at 15 m bathymetry at coordinates 32° 10 'S and 51° 58' W, east of the pier in front of the Port of Rio Grande. After anchoring, the data were collected for ten consecutive months, until August 1997. During a storm, broke up the anchor and buoy drifted. Yet another interruption occurred in April 1998. Measurements were closed earlier in the year 2000.

Finally, a preliminary data base establishing the behavior of waves in the region of Rio Grande was obtained. Figure1 shows the float (left) and its release (right). Figure 2 shows its location on the map.

Figure 1. Wave rider buoy, left, and release of buoy, right, in October 1996 [8].

The characteristics of the entire coast of Rio Grande do Sul are very similar along about 620 km from Torres almost to the southern boundary of the State. The path from Torres to the southern boundary of the State can be located on Google Maps [9] at goo.gl/maps/lcRM5. This characteristic of the coast suggests that these results are valid over the entire region. Obviously, specific studies should be performed to determine in more detail the energetic potential of the region.

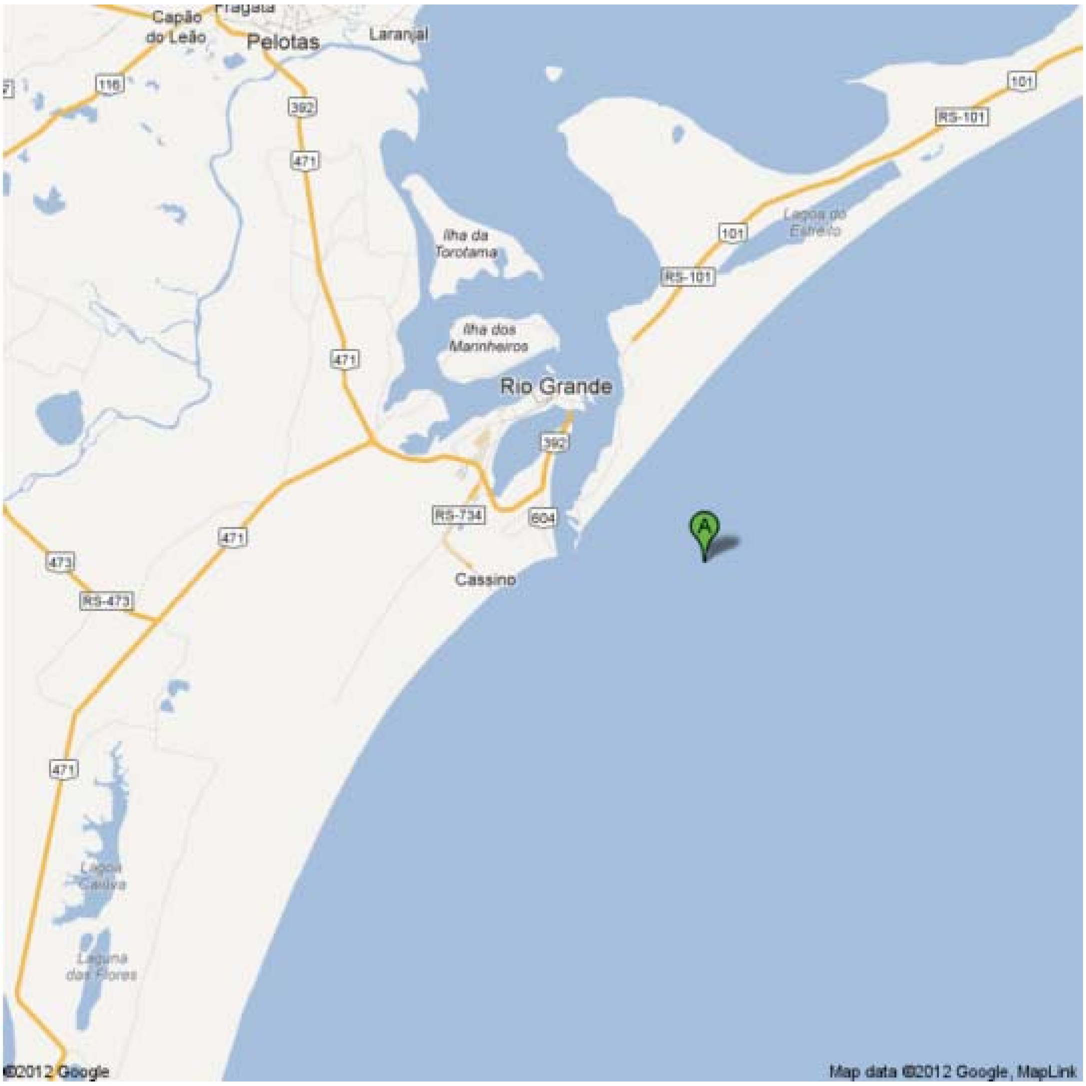

Figure 2. Location of wave rider buoy in front of Rio Grande, at point A, on the coast of Rio Grande do Sul. This location can be accessed directly at goo.gl/maps/MEAQt [9].

4. Results and discussion

The data provided information concerning the direction of propagation of the waves, the significant height, period and peak power of the waves. The data range considered is from January 1996 until December 1999.

The results for the energy resource monthly, seasonal and yearly for the region considered in this study are presented in Table 1. Figures 3-6 show the results respectively for the months of southern hemisphere autumn, winter, spring and summer.

The data analysis revealed an annual average of 8.6 kW per meter of wave front. An analysis by season reveals that occurs during the southern hemisphere fall an average of 11.6 kW/m, while in southern hemisphere spring the average reaches 7.4 kW per meter of wave front. The results are somewhat more shy than the results shown by Thorpe [10].

A monthly analysis shows that the month of May has the highest monthly average with 14.2 kW per meter of wave front. The months from February to June showed the best monthly averages. The month of January was the lowest monthly average, with 4.2 kW per meter of wave front.

The results indicate good perspectives in obtaining power supplies. In a simple example implementation, an average of 8.6 kW/m, assuming a final efficiency of approximately 30%, would lead to a plant with 2.58 MW to 1000 meters in length. Obviously there are environmental impacts associated with this type of energy conversion process, which should be compared to the benefit or need to use this energy resource.

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Table 1. Average monthly, seasonal and annual values of $\overline{H}_S$ [m], $\overline{T}_e$ [s] e P [kW/m] obtained for the data series from January 1996 to December 1999

	Monthly			Seasonal			Annual		
	Hs [m]	Te [s]	P [kW/m]	Hs [m]	Te [s]	P [kW/m]	Hs [m]	Te [s]	P [kW/m]
Jan	1.23	5.30	4.02						
Feb	1.73	5.90	8.82	1.62	5.80	7.70			
Mar	1.72	6.20	9.17						
Apr	1.97	6.02	12.00						
May	2.06	6.70	14.20	1.88	6.04	11.35			
Jun	1.71	6.54	9.60				1,68	5,96	8.60
Jul	1.33	6.00	5.30						
Aug	1.73	6.33	9.50	1.60	6.30	8.06			
Sep	1.45	5.90	6.20						
Oct	1.63	5.90	7.90						
Nov	1.70	5.60	8.10	1.61	5.71	7.04			
Dec	1.60	5.60	7.17						

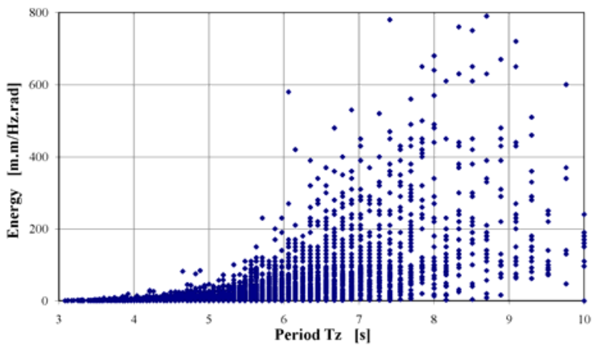

Figure 3. Energy [m.m/Hz/rad] as a function of period Tz [s] for the southern hemisphere autumn

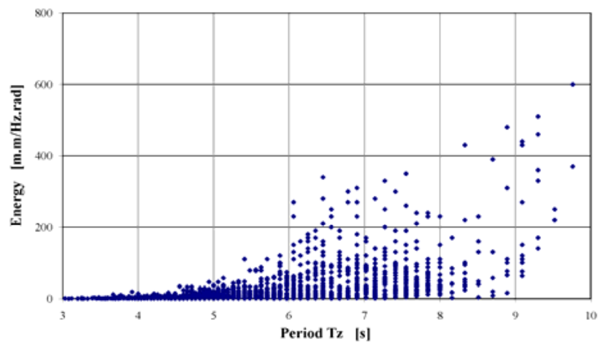

Figure 4. Energy [m.m/Hz/rad] as a function of period Tz [s] for the southern hemisphere winter

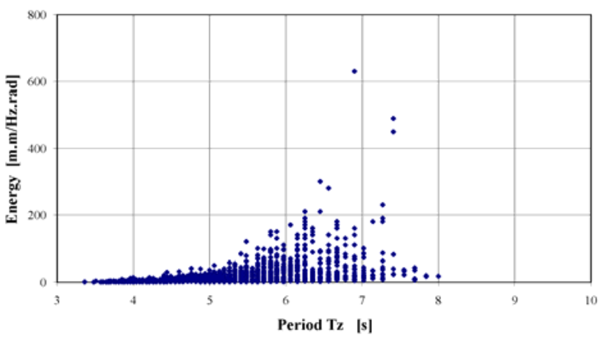

Figure 5. Energy [m.m/Hz/rad] as a function of period Tz [s] for the southern hemisphere spring

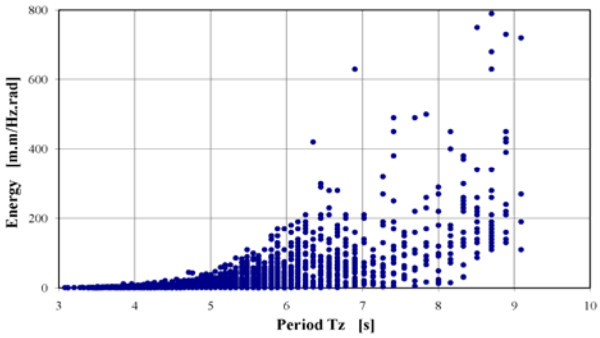

Figure 6. Energy [m.m/Hz/rad] as a function of period Tz [s] for the southern hemisphere summer

5. Conclusions

The study aimed to preliminarily evaluate the potential for generating energy from ocean waves based on data obtained with a wave rider buoy. The data analysis revealed an average annual output of 8.6 kW available per meter of wave front. An analysis by season reveals that occurs during the fall an average of

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11.6 kW per meter, while in spring the average reaches 7.4 kW per meter of wave front. A monthly analysis shows that the month of May has the highest monthly average with 14.2 kW per meter of wave front. The months from February to June showed the best monthly averages. The month of January was the lowest monthly average, with 4.2 kW per meter of wave front. The results indicate good perspectives in obtaining power supplies.

The continuity of the research should consider some important aspects, in addition to installation of buoys at various positions along the study area, for obtaining longer series of data.. The results deserve a more careful analysis regarding the possible complementarity in time with solar energy and the possible spatial complementarity with hydro energy [11-13]. The operation in conjunction with a reversible hydro power plant may lead to increase in capacity factor of power plants based on renewable resources [14]. It is also possible that there is a natural complementarity between wind and wave energy.

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