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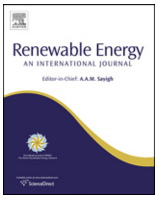

Wave energy resources: Wave climate and exploitation

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ABSTRACT

In identifying the most convenient zones for harvesting wave energy, it is natural to be attracted by the areas where we find the highest mean energy values. The obvious examples are the storm belts. A more careful analysis reveals that for practical use other factors need to be taken into account. Some of the main ones are the energy spread in frequency and direction, and its seasonality, without discussing the cost of the structure basically related to the conditions to be withstood. This reveals that other areas, in particular the equatorial ones, can be conveniently used, and be possibly advantageous from various points of view. Based on the results of the ECMWF ERA-Interim reanalysis and of altimeter data, we have carried out a comparative analysis between two locations with opposite characteristics, in the North Atlantic and in the Equatorial Pacific respectively. The quantified results confirm that less energetic, but more regular and less extreme, areas have a potential comparable to that of the classically considered storm belts.

1. Introduction

Harvesting wave energy from the ocean is obviously a subject of interest. Taking for granted the present level of related technology (e.g., [1–4]), it is necessary to establish which are potentially the most promising areas. At a first glance, it is natural to associate these areas to the parts of the ocean where we find the highest levels of wave energy. In this paper, we show that a deeper analysis of the situation is required for an optimal choice, both from the point of view of production and for the related economic analysis.

There are many challenges involved in the practice of wave energy harvesting. Some of them are technical, because the nature of wave energy is oscillatory, while standard technologies for electricity production involve rotational or linear generators. Wave energy converters (WEC) are conceived for carrying out this transformation. Others challenges are environmental, because wave energy does not come in a regular form. A normal sea state is composed by the superposition of a number of monochromatic waves. In order to convert energy efficiently, ideally an optimal WEC should be able to interact with all of the small and large wave components. In practice, from a more realistic point of view, WECs are restricted to work in specific ranges of frequencies and directions (e.g., see Ref. [5]).

Other challenges involve the harsh environmental conditions at sea. WECs are exposed to corrosive saline water and to strong forces inherent to the water motion. In comparison to air for wind energy, the water density is three orders of magnitude larger and its associated energy is proportionally higher. However, the forces on the mechanisms and the related construction costs increase as well, generally with a power >1. For this reason, WECs cannot operate under strong wave conditions. Whenever a high sea state is expected, the device has to stop operations and protect itself, going in the so-called survival mode. On the other hand, WECs cannot operate if the energy is too low. A minimum of energy is necessary to start-up the system.

These aspects naturally affect the performance, and therefore also the economical return of a related project. Apart from the WEC technological complexity and the variety of concepts developed to convert wave energy into electricity, several issues affecting WEC operation can be associated with the wave climate, which is the focus of this study. The advantage is that at present many environmental variables are understood with a very good degree of confidence. Wave variables in particular, are routinely monitored from space and forecast by numerical models. In addition, meteorological centres like the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, U.K.) archive data over long periods of time.

In this paper we carry out a comparative evaluation of wave energy resources, taking into account aspects, like those mentioned

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above, that can be linked to the wave climate. Namely, we focus our attention on the distribution of energy over frequency and direction, and on the start-up and survival conditions. These considerations are accounted for by straightforward parameterizations established from the perspective of the wave climate.

The paper is organized in six sections. In Section 2 we describe the main data sources, in Section 3 the general background for the calculation of the wave power is briefly presented, in Section 4 we define the statistics required for the description of the wave climate in the selected areas, and Section 5 contains the evaluation of the wave resources considering the above aspects. The output is translated into standard economical parameters like the annual production and the capacity factor to make the link with engineering applications. Finally in Section 6 a brief discussion summarizes our main findings and conclusions.

2. Data sources

Two data sources are used in this study. Namely, wave model results from ECMWF, and significant wave height (Hs) data from satellite altimeters. Altimeter data is very attractive (see, e.g., [6,7]). There is a practically global marine coverage and data is available with continuity since the early '90s. Global Hs distributions have been derived, among them the one by Young and Holland [8] and the permanently updated one by Oceanor [9]. However, a strong limitation is that the information contains only Hs. Some attempts have been made to also derive wave period (see, e.g., [10]), but without much conclusive evidence, particularly in swell dominated areas. In any case, altimeter data lacks the fundamental information about direction. This limitation is very restrictive, since a correct assessment of the wave energy requires the knowledge of its distribution in frequency and direction. The Synthetic Aperture Radar (SAR) could in principle overcome this. However, sparseness in time and space, as is the case for altimeters, is inherent to this data. Moreover, other limitations apply to the SAR data. The first one is the rather low cut-off frequency, only sufficiently long waves can be observed accurately, see Refs. [11,12]. The second is the directional ambiguity, the SAR imagette from which the spectrum is derived is a frozen picture of the moving sea surface and therefore ambiguous over 180°. Although several studies have been conducted to tackle this aspect (e.g., [13,14]), this is still an open issue.

The alternative data source, model results, has quite different characteristics, the main one being its continuity and homogeneity both in time and space. This adds to the fact that it is possible to assemble large model data-sets from historical runs (hindcasts). At present, numerical wave models are very robust and include the most relevant physical processes of the wave evolution, (see Refs. [15–18]). The obvious solution is to make use of both the sources, complementing the sparse and discontinuous, but measured, altimeter data with the continuous and homogeneous model one.

For the present study, we use the ECMWF data derived from the ERA-Interim archive [19,20]. ERA-Interim is a reanalysis project aimed at providing long-term meteorological and oceanographic data with uniform accuracy and sufficient resolution. The ERA-Interim reanalysis products have been extensively validated and verified (see, among others [21–24]). These and other studies have shown the high quality of the model data, both for meteorological and wave parameters.

The wave model operational at ECMWF is WAM Cycle IV [15,25,26]. WAM is a state-of-the-art spectral wave model used at several meteorological centres around the world. WAM solves the wave energy balance equation defined in the spectral domain. For ERA-Interim the wave spectrum is discretized into 24 directions and 36 frequency bins. The frequency ranges from 0.0345 to 0.5476 Hz in geometric sequence, and the directions from 7.5° to 352.5° in steps of 15° (see Ref. [27] for details). Deep-water source terms account for wind input, non-linear resonant interactions, and white-capping dissipation. The data has global coverage with a spatial resolution of 0.5° in latitude and longitude. Although the wave spectrum is the actual variable of the model, it is typical to provide users with outputs in the form of integral parameters like significant wave height (H_{m0}), mean wave period ($T_{m-1,0}$), and mean wave direction (θ_m). The wave power, object of this study, is another integral parameter of the wave spectrum and can therefore be obtained accordingly (see Section 3). The period we considered covers 21 years from 1989 to 2010. This relatively long time series is necessary in order to be statistically representative.

For the comparison between model and altimeter data, the following statistical parameters are considered: bias, root mean square error (RMSE), and scatter index (SI) defined as follows:

$$\mathrm{BIAS} = \frac{1}{N}\sum_{i=1}^{N}(y_i - x_i) \tag{1}$$

$$\mathrm{RMSE} = \left\{\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right\}^{1/2} \tag{2}$$

$$\mathrm{SI} = \frac{\mathrm{RMSE}}{|\bar{x}|} \tag{3}$$

with x the measured and y the model data.

We use data from three different altimeters, ENVISAT, Jason and Jason-2, their orbits have (had for ENVISAT) different characteristics with return time of 31 days for ENVISAT, and 10 for the Jason's. This corresponds to an equatorial distance between adjacent orbits of 90 and 277 km respectively. For our discussion and to analyse different wave climates, we focus our attention on two areas, one in the North Atlantic (NA), and the other one in the Equatorial Pacific (EP). The different latitudes of the considered areas lead to a different, larger in the case of the NA, number of altimeter data.

Notwithstanding the previous validation of the ERA-Interim reanalysis results (see the already quoted references), we have chosen to carry a devoted validation in the two areas of interest. Therefore, altimeter data concerning NA and EP have been co-located with the corresponding wave model results. The co-location areas correspond to boxes of 20° in latitude and longitude centred at the analysis points (see Table 1). The overall results of the comparison are reported in Fig. 1 and Table 2. At a summary look, it is clear that the low values of bias, RMSE and SI ensure that model data can be used confidently for the present purposes. Nevertheless, it is worthwhile to point out some of their characteristics. The bias values reveal some differences among the three altimeters, a fact already discussed in the literature (see, among others, [22]). The results in Table 2 suggest that ENVISAT provides on average larger Hs, whence a negative bias of the model. The larger RMSE values at NA reflect the higher, on average, Hs at this location. Possibly the larger biases at EP derive from the less accurate, with respect to the storm belts, modelling of the propagation and possible attenuation of swell over large distances, see Refs. [15,28] for discussion on the subject. Note, however, how these

Table 1
Geographical coordinates of the considered locations.

name	Area	Longitude	Latitude
NA	North Atlantic	26°W	40°N
EP	Equatorial Pacific	93°W	1°S