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Wave energy and nearshore *hot spots*: The case of the SE Bay of Biscay

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A B S T R A C T

The wave energy resource of the SE Bay of Biscay is investigated using wave buoy data and a hindcast data set covering a 44-year period (1958–2001). Of the total 13 study sites, three correspond to wave buoys (two coastal, one in deep-water) and the rest to hindcast data points. First, the resource is quantified—annual wave energy is found to exceed 200 MWh m^{-1} at all the sites (with the exception of the coastal buoys), and average wave power is in the region of 25 kW m^{-1}. This substantial resource is the result of the Bay of Biscay's position at the eastern end of the Atlantic Ocean together with the wind regime of the mid-latitudes (prevailing westerlies). Second, the resource is characterised in terms of sea state parameters. The bulk of the annual wave energy is provided by waves with significant wave heights of 1.5–4.0 m, energy periods of 10.5–13.5 s, and mean deep-water direction NW–WNW. Finally, wave interaction with the irregular bathymetry gives rise, in certain nearshore areas, to significant concentrations of wave energy. These hot spots have the highest potential as prospective wave farm sites; their locations are determined using numerical modelling.

1. Introduction

The objective of increasing the contribution of renewable energy sources to the total energy production can only be achieved by developing different renewable energies in accordance with the resources of each region. In the coastal regions subjected to a harsh wave climate, such as the Bay of Biscay, wave power is poised to be one of the pillars of the development of renewables.

The Bay of Biscay, named for the eponymous Spanish province, is a gulf in the NE Atlantic Ocean defined by the northern coast of Spain and the western coast of France—from Cape Estaca de Bares in Galicia eastward to the French border, and from there northward to the tip of Brittany (Finistère). Like other regions of the northern seaboard of Iberia, notably Galicia [1–4], the Bay of Biscay offers a clear potential for wave energy exploitation for two main reasons. First, it lies at the eastern boundary of a long oceanic fetch stretching to America. Second, westerly winds prevail in these mid-latitudes throughout the year.

Given the large dimensions of the Bay of Biscay, this work focuses on the south-eastern section, from Ría de la Tina Mayor to the French border (Fig. 1)—some 300 km of coastline corresponding to the Spanish regions of Cantabria and the Basque Country. Its wave energy resource was assessed based on wave data from three directional wave buoys and an extensive hindcast data set covering 44 years (SIMAR-44), from which the ten points strung along the coastline of the SE Bay of Biscay are chosen. The annual wave energy for an average year and the average power (or average energy flux) at the 13 study sites were computed.

For all their interest, neither the annual wave energy nor the average wave power describe the characteristics of the wave energy resource in terms of the sea states providing it (i.e. in terms of wave parameters). This characterisation is important for choosing the most appropriate Wave Energy Converter (WEC) for the area, for tuning an existing WEC design, or perhaps even for designing an ad hoc device—WECs must be adapted to the local wave climate if they are to be competitive [5]. With this in view, the wave energy resource was characterised in terms of significant wave heights, energy periods, and mean directions.

As regards the selection of prospective locations for a *wave farm*, both nearshore and offshore locations may be envisaged. In fact, it is the economics that will (mostly) dictate which alternative is chosen, taking into account the differences in the resource [6] and the cost of the submarine connection to the land network. The economics of building and operating a *wave farm* is a complex matter, and one that depends greatly on public policy issues (e.g. fiscal incentives). This is, however, outside the scope of this work; of interest here is an important factor that should be considered in the selection of possible nearshore sites—wave transformation

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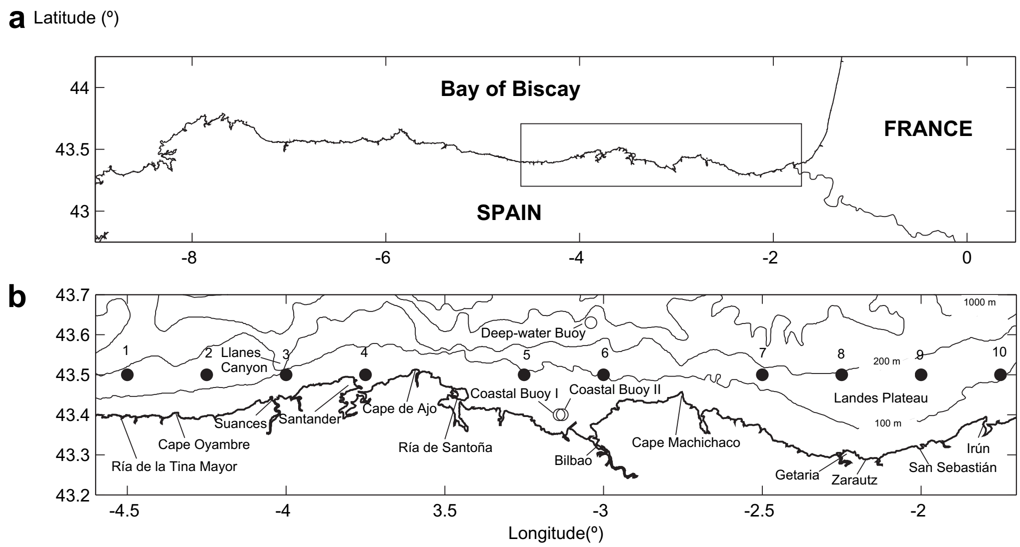

Fig. 1. Coastline of N Spain (a) and study area with the location of the wave buoys and SIMAR-44 points (b).

in intermediate and shallow waters. Wave properties change as waves interact with the irregular bottom contours in their propagation towards the shoreline, experiencing refraction and shoaling [7,8]; this interaction gives rise to an irregular distribution of wave energy in the nearshore, with areas of energy concentration (*hot spots*) and, on the other side, areas of relatively low energy (*cold spots*). It is clear that, within the nearshore alternative, *hot spots* should be favoured as wave farm sites. In order to determine their locations in the SE Bay of Biscay, the SWAN coastal wave model [9] was implemented on a Cartesian grid, successfully validated based on wave buoy data, and applied to three case studies representative of typical spring–summer and winter–autumn conditions, and of storm conditions. From the results of these case studies emerge the nearshore *hot spots* with the highest potential as *wave farm* sites.

2. Wave data

2.1. Wave buoys

Observations from a deep-water and two coastal directional wave buoys were used (Fig. 1, Table 1). The deep-water buoy (SeaWatch™ since December 2006; previously Wavescan™) is located roughly 33 km north of the Bilbao harbour, in 600 m water depth. The data set from this buoy extends from 1990/11/07 to 2009/05/15, with hourly data. The locations of the two coastal buoys (Triaxys™) are very close to each other, at a water depth of 50 m and in proximity to the Bilbao harbour. The periods of time covered by each of them are different, except for a small overlapping: in the case of Coastal Buoy I, the data set extends from 1985/02/21 to 2005/04/11; in the case of Coastal Buoy II, the data set covers the period from 2004/02/26 to 2009/05/15; in both cases, data were recorded hourly. The three wave buoys are (or were, in the case of Coastal Buoy I) operated by Puertos del Estado (Spain's State Ports).

2.2. SIMAR-44 data set

In addition to the wave buoy data, hindcast data from the SIMAR-44 data set [10] were used. This data set, successfully applied in previous wave energy assessments and assessment methodologies [2,3,11,12], covers an extensive period of time: from 1958 to 2001. It was obtained using the WAM cycle-4 (a.k.a. WAMC4) third generation spectral wave model [13,14], forced with wind fields obtained by means of the REMO regional atmospheric model in the context of the HIPOCAS project [10,15,16]; the REMO model was forced with data from the global atmospheric reanalysis carried out by the U.S. National Center for Environmental Prediction (NCEP) integrating instrumental and satellite data. The grids for the WAM and REMO models covered the North Atlantic with a resolution of $0.5^\circ \times 0.5^\circ$, increased to $0.25^\circ \times 0.25^\circ$ near the coastline. The 10 grid nodes close to the coast of the SE Bay of Biscay were used for this study. Their coordinates and locations are shown in Table 2 and Fig. 1, respectively.

3. Wave energy assessment and characterisation

The main parameters from the standpoint of wave energy for the wave buoys and SIMAR-44 points are presented in Tables 1 and 2, respectively. Of particular interest is the annual wave energy, which was computed based on an average year; it is in the range 200–250 MWh m^{-1} at all the study sites with the exception of the coastal buoys—located in relatively shallow water and, above all, in an area partially sheltered by the coastline configuration from the IV quadrant waves that, as will be seen, provide most of the energy in the SE Bay of Biscay. The significant wave heights are again similar at all the study sites (in the order of 1.8 m), and so are the mean wave power values (in the order of 25 kW m^{-1}), again with the exception of the coastal wave buoys. All in all, the wave energy resource in the SE Bay of Biscay is substantial, albeit slightly inferior to that of Galicia (NW Spain) [1].

Table 1
Location and main parameters of the wave buoys.

Site no.	Location	Depth (m)	$(H_{m0})_{mean}$ ± std. dev. (m)	$(H_{m0})_{max}$ (m)	H_{max} (m)	J_{mean} (kW m^{-1})	J_{max} (kW m^{-1})	$(E)_{annual}$ (MWh m^{-1})
Deep-water Buoy	3.04°W, 43.63°N	600	1.90 ± 1.12	13.4	22.6	25.84	1443.0	226.51
Coastal Buoy I	3.14°W, 43.40°N	50	1.45 ± 0.83	8.2	12.9	15.69	593.1	137.53
Coastal Buoy II	3.13°W, 43.40°N	53	1.37 ± 0.80	8.4	15.3	12.63	591.0	110.75