Renewable Energy 96 (2016) 20–32

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Wave energy potential along the Atlantic coast of Morocco

J.P. Sierra [a, b, *], C. Martín [a], C. Mösso [a, b], M. Mestres [a, b], R. Jebbad [a, b]

[a] Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya, Jordi Girona 1-3, Mòdul D1, Campus Nord, 08034, Barcelona, Spain
[b] Centre Internacional d'Investigació dels Recursos Costaners, Jordi Girona 1-3, Mòdul D1, Campus Nord, 08034, Barcelona, Spain

ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form
11 March 2016
Accepted 24 April 2016

Keywords:
Wave energy
Morocco
Hindcasting
Atlantic coast
Wave energy converter

ABSTRACT

This study analyses the wave energy resource along the Atlantic coast of Morocco using a 44-year series of data obtained from numerical modeling (hindcasting). The spatial distribution of wave power is analyzed using data from 23 points along that coast. The estimated resources (average wave power up to 30 kW/m and average annual wave energy up to 262 MW h/m) are considerable and slightly lower than at the neighboring Canary Islands. The central part of this area (between latitudes 29°30′N and 34°N) is the most productive, while in the northern and southern parts the resource is significantly lower due to the shadow effect of the Iberian Peninsula and the Canary Islands, respectively. The study of the temporal variability indicates a considerable seasonal trend, being the wave energy resource over four times greater in winter than in summer. Moreover, the power matrices of two wave energy converters (WECs) are considered to estimate the average power output at all the studied points. Finally, a multi-criteria analysis is carried out considering five different factors in order to select the best places for WEC deployment.

1. Introduction

The energetic needs of the planet are continuously growing due to the increase of population and the emergence of new energy-demanding activities. This is particularly critical in emergent counties like Morocco, in which this situation might be aggravated by the lack of fossil fuel reserves. As a consequence, the development of renewable energies in emergent countries is crucial for both environmental and economic issues.

According to data from 2012 [1], about 90% of the energy production in Morocco is from thermal origin, while the other 10% is from renewable sources, mainly hydraulic and wind energy. The energetic sector shows a large dependence from external energy sources, which account for 97% of primary energy sources and 15% for electric power [1].

Morocco presents a high potential for renewable energies, and some studies have analyzed the availability of energies due to wind [2–4] and solar radiation [5,6] in this country. Nevertheless, as far as the authors know, there are no specific studies addressing the potential of wave energy there.

Some studies assessed the wave energy resource in the whole Mediterranean. Thus [7], found at the Mediterranean Coast of Morocco wave energy powers between 2 kW/m and 6 kW/m, while [8] estimated a mean wave power of 6.3 kW/m at a point in the Moroccan Mediterranean.

A number of studies have assessed the wave resource in islands located in the Atlantic Ocean, not far from the Moroccan coast, like the Canary Islands [9–12], Madeira [13,14] or Azores Islands [15], or all of these plus Iceland [16]. Other research has focused on the Northeast Atlantic, mainly in the United Kingdom [17–19], France [20,21], Portugal [22–24] and Spain [25–28] or several places at a time [29]. These studies found a considerable potential of wave energy in those areas. Moreover, it was estimated that the annual gross theoretical wave power is more significant on the western coasts of the continents, due to the prevalence of west-to-east winds [26,28–32].

Considering the potential of nearby areas, wave energy could be a good alternative to reduce the dependence of Morocco on fossil fuels, as well as to contribute to reduce greenhouse gas emissions. Moreover, besides energy generation, wave-energy farms can be used for coastal protection in order to limit erosion processes [29,33].

This paper focuses on the assessment of wave power potential and wave energy yield around the Atlantic coast of Morocco. Section 2 briefly describes the study area and presents the available

* Corresponding author. Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya, Jordi Girona 1-3, Mòdul D1, Campus Nord, 08034, Barcelona, Spain.
E-mail address: joan.pau.sierra@upc.edu (J.P. Sierra).

http://dx.doi.org/10.1016/j.renene.2016.04.071
0960-1481/

data and the methodology used. In Section 3 the wave energy resource along the Atlantic coast of Morocco is assessed, while in Section 4 the results are discussed and the best places for deploying Wave Energy Converters (WECs) are identified. Finally, the conclusions of the paper are presented in Section 5.

2. Data and methods

2.1. Study area and available wave data

Morocco, located in the northwest of Africa, has a long coast (more than 1800 km) facing the Mediterranean Sea (from the Algerian border to the strait of Gibraltar) and the Atlantic Ocean (from this strait to the limit of Western Sahara). This last stretch is the study area (27°40′–35°48′N, 13°11′–5°53′W) with an approximate length of 1300 km (Fig. 1).

Waves arriving at the Moroccan Atlantic coast have their origin in the Azores islands, where winds of large intensity and duration generate high waves that propagate for long distances, reaching that coast in around 30 h [34]. During their propagation, these waves are deviated to the right arriving almost perpendicular to the coast and reducing their power [35]. On the northernmost part of this coast, waves are reduced by the shelter provided by the SW corner of the Iberian Peninsula. On the southernmost area, the Canary Islands also contribute to reduce the magnitude of the incoming waves.

The data used for this study correspond to the 44-year hindcasting wave climate database (1958–2001) from the European HIPOCAS project [36,37]. This wave data set was obtained using the WAM model [38] forced by the wind output of the REMO regional atmospheric model [39], which in turn was forced by the global atmospheric reanalysis carried out by the U.S. National Centers for Environmental Prediction (NCEP). The HIPOCAS database has been extensively validated for wind, wave and sea-level parameters [40,41]. This simulation, like most, has some limitations in terms of properly reproducing certain storm events, but it generally reproduces mean values quite well [42]. With a resolution of 0.25° X 0.25° and three-hourly data, this database offers homogeneous long-term data and a higher spatial coverage than that obtained with single-point observations (e.g. buoys). Moreover, data from the HIPOCAS project have previously been used to characterize wave energy potential in various areas [10,26,27,30,31].

A total of 23 points are analyzed for investigating their wave energy potential. The location of these points is presented in Fig. 1, while their geographical coordinates, water depths and distances to the coast are provided in Table 1. These last two data were obtained from nautical charts and the values shown in the table are only approximate. It can be noticed that all the points, except P17 (35 m) and P20 (40 m) have water depths greater than, or equal to 50 m. On the other hand, the distances to the coast are very variable, ranging from 5 km (P1) to 52 km (P6 and P19), with 14 points being located at distances smaller than 25 km while the other 9 are farther away from the coast. Although some distances could seem too large, they can be considered viable for a future farm location since they are deemed feasible for the offshore wind industry, with some projects operating (or planned to be installed) at distances from the shore between 79 and 112 km [29].

2.2. Methodology

Wave power can be obtained using the following deep-water expression:

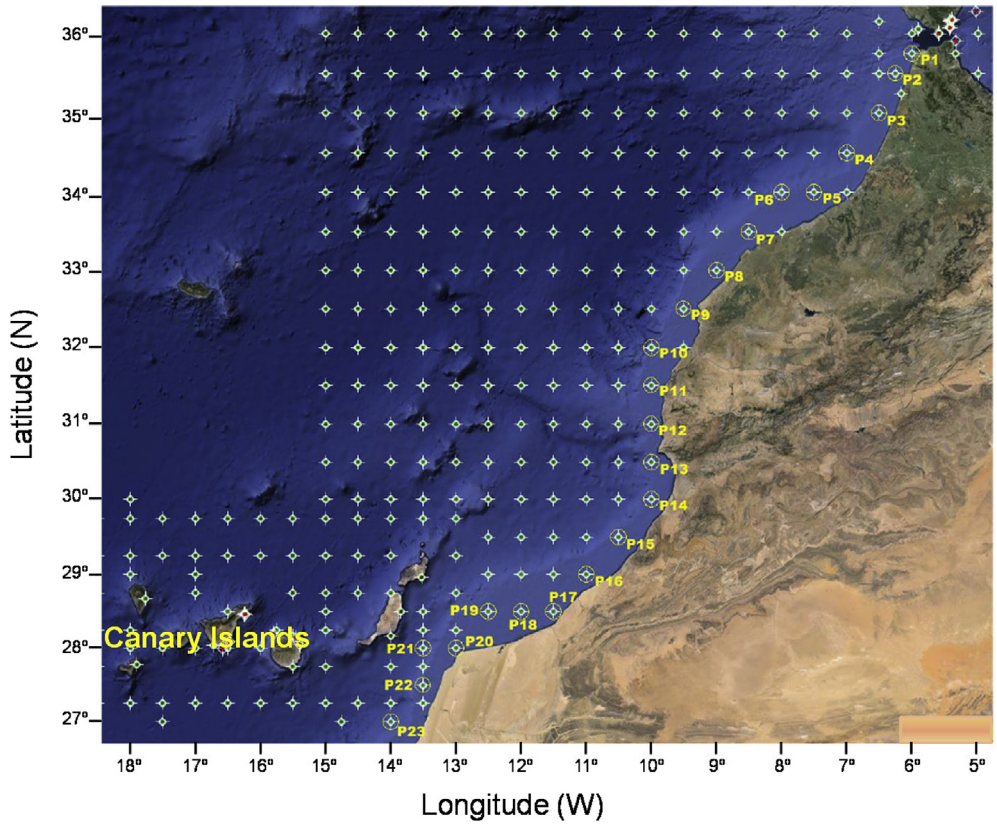

Fig. 1. Map of the Moroccan Coast with the location of the 23 studied points.