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Assessment of the performances of various wave energy converters along the European continental coasts

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ABSTRACT

The present work aims to provide a realistic picture of the efficiency along the European continental coasts of ten representative wave energy converters. The main coastal environments targeted are the western sides of Scandinavia, Ireland, UK, Iberian Peninsula and also the Mediterranean and Black seas. In order to evaluate the wave climate corresponding to these coastal areas, several reference points, located at about 50 m water depth, were defined. An analysis of the wave conditions in the target areas has been performed by considering 11-year of hindcast wave data (January 2003–December 2013) provided by the European Centre for Medium-Range Weather Forecasts. At that point, the analysis was focused on the evaluation of the main wave parameters, including the expected average wave power. Thus, for all coastal environments and wave energy converters considered, besides the expected electric power and the capacity factor, some other indicators (as the normalized power) have been also evaluated. The results show that in general the converters with a nominal power greater than 2000 W can generate a significant amount of electricity, compared to the systems rated below 1000 kW, which instead appear to have higher values of the capacity factor, especially during the winter season.

1. Introduction

In a simple analysis of the European energy market, it can be noticed that the EU countries consume one fifth of the global oil and gas supplies, which cannot be considered beneficial for the near future given the fact that this region has limited fossil fuel deposits. In fact, every year nearly 350 billion Euros are spent to buy petroleum and products from Russia, Iraq or OPEC (Organization of the Petroleum Exporting Countries) [1]. As an alternative, the natural resources from Europe are already used in various projects as: the offshore wind farms from Denmark, the wave farms from Portugal or the Iron Gate dams and onshore wind farms from Romania [2,3]. There is an upward trend to develop such projects in the European countries and if we look at the gross inland consumption, it can be noticed that almost 5% was accounted by renewables in 1999, while in 2011 this sector reached 10% of the total energy mix [4].

From all the renewable energy sources, those located in the marine environment can be considered to be the most promising since they are characterized by higher power density and consistency and allow a more accurate forecast of the conditions over both short and long term time periods [5–7]. Another advantage results from the existence of large water areas, which can be used to develop large marine energy parks without major limitations, the current impediments being related mostly to the water depths, the storm conditions or the restricted areas. The European offshore wind industry represents already an important market, being estimated that in 2014 and 2015 the existing capacity will increase by almost 3 GW through the 12 projects under construction, which will set the cumulative capacity to 9.4 GW [8]. Although the wind industry is presently more developed, the sea waves are considered to be more energetic. They are in some sense a concentrated form of the wind power, which is carried out over large distances with minimum energy loss. It was estimated that the annual gross theoretical wave power is more significant on the western coasts of the continents (due to prevailing winds from west to east), with values of the wave power over a meter of wavelength close to: 60 kW/m in Scandinavia, UK or Australia; 40 kW/m in the extremity of the Iberian Peninsula; and 5–10 kW/m in Mediterranean, Black or Caspian seas, respectively [9–14].

In Europe, some important projects are currently ongoing (as for example DTOcean, SI Ocean, MARINET or SOWFIA), which are

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focused on the industrial development of the ocean energy power generation by gathering partners from various countries, as: Ireland, UK, Danemark, Portugal or Germany. The first commercial wave power project was the Aguçadoura project opened in 2008 on the Portuguese coast, which was started with three Pelamis systems. Other projects under development in which the Pelamis Wave Power Company is involved are Farr Point, Aegir or Bernera. Since some of the EU countries as Ireland, UK or Portugal present good conditions for wave energy extraction, some other projects are also focused on the Portuguese mainland and the island areas, and also in countries as Canada, Australia or South Korea [15], or on the Portuguese archipelagoes (Madeira and Azores), where it is intended to develop Wave Dragon farms with a total capacity of 50 MW.

According to the European Marine Energy Centre at this moment several countries are involved in projects which are focused on the development of the WEC (wave energy converters) industry, as follows: UK (26 projects), Norway (14), Denmark (9), Spain (9), Ireland (7), Sweden (5), France (4), Finland – Germany – Portugal (2), Greece (1).

Various WEC (wave energy converters) systems have been developed during the last decades, some of them being designed to perform also in enclosed sea basins, which are characterized by significant wind conditions [16,17]. From this perspective, the Eastern Mediterranean and Aegean seas are considered representative areas, which in general present along their coasts an average wave power of 2 kW/m and increasing close to 4 kW/m around the Greek Islands, while an energetic sea state is represented in this environment by a significant wave height of 4 m and a wave period in the range of 4–8 s [18]. On a regional scale, another significant basin is represented by the Black Sea area, where previous analyses indicated more energetic wave and wind conditions in the western side of the sea [19,20]. In this area, in the case of an extreme event the maximum wave power can reach 143 kW/m, value which is related to a significant wave height of about 7 m [21].

In this context, the main objective of the present work is to investigate the wave energy potential in the most representative European nearshore areas and also to evaluate the expected performances of some representative WEC systems, which might operate in the near future in these regions.

2. Methods and materials

2.1. Target areas

Fig. 1 presents the distribution of the reference points (denoted from P1 to P21), which are distributed along four different European continental coastal environments. The first three points are located in the northern part of Europe, in the vicinity of the Scandinavian region (zone A), followed by the group of points P4–P9, which were chosen along Ireland and UK (zone B). The points P10–P15 were considered in the southwestern part of Europe, more precisely close to France and Iberian Peninsula (zone C). In order to assess also the potential of some enclosed seas, the last six points were chosen along the EU coasts from the Mediterranean Sea (P16–P18) and the Black Sea (P19–P21), all of them included in the zone D.

More details regarding the coordinates, the distance to shore and the water depth, corresponding to the reference points considered, are presented in Table 1, from which it can be noticed that the main selection criteria is represented by the water depth which was set close to 50 m, this being in the range of depths where most of the offshore WEC systems considered are rated to work. The approximate distances to the shoreline are also presented, since they represent an important factor for an early development of a wave farm project. From this perspective, it can be also noticed that a minimum value of 2.9 km is reported by the point P17 while a maximum of 79.4 km is indicated by the point P5. Although at a first sight this last distance seems to be too large, it can also be considered viable for a future wave farm location. This especially if we take into account that such distance is currently considered viable for the offshore wind industry, where already some projects operate (or are planned to be installed) at similar distances, as for example: BARD Offshore 1 (Germany – 112 km), Global Tech I (Germany – 109 km) or Brown Ridge Oost (The Netherlands – 79 km) [22].

2.2. Reanalysis dataset

The most up-to-date reanalysis product of the ECMWF (European Centre for Medium-Range Weather Forecasts), namely the ERA-Interim reanalysis dataset, was considered in the present study. This is a global wind and wave dataset produced by a coupled atmosphere-wave model, available from 1979 onwards. The newly available dataset was obtained by improving the physics of the models used in the earlier ERA-40 reanalysis data, and also by using additional observations and updated assimilation techniques. The ERA-Interim data assimilation system was released in March 2009 and uses a 2006 version of the Integrated Forecasting System (IFS Cy31r2), which presents significant improvements in the analysis methodology and forecasting model, respectively of the previous version [23]. The reanalysis system involves a sequential data assimilation process, which uses an advanced forecasting scheme with a 12-hourly analysis cycle. During each loop, the observations available are combined with previous data from the forecasting model to evaluate the evolving state of the global atmosphere. This means in the first phase a computation of various atmospheric parameters (ex: wind, temperature or humidity), which is followed by a separate analysis of the near surface characteristics (ex: sea waves or snow) [24,25].

In the present study, the following wave characteristics were considered for analysis: a) significant height of combined wind-waves and swell (*Hs*); b) mean wave period (*Tm*) and c) mean wave direction (*Dir*). Each parameter is daily reported with a 6-h time step (00–06-12–18 UTC), and a spatial resolution of $0.75° \times 0.75°$. The data set considered covers the 11-year interval January 2003–December 2013. For each wave parameter, the results were interpolated from the grid points to the reference points using bilinear interpolations.

2.3. WEC systems

Since the sea waves release their energy under various forms (kinetic or potential), this power can be harnessed in different ways, which means that each WEC manufacturer uses a different approach to produce an efficient and reliable system. In Table 2 the main characteristics of ten different WEC devices are presented. These are further considered in the present study to assess their performance in different European coastal regions. All these systems were designed to work in the offshore areas, some of them being already in the commercial stage while others are currently in the phase of testing in real sea conditions.

As it can be noticed also from Table 2, various WEC classifications can be made according to their principle (as point absorber, attenuator or terminator), size, rated capacity or recommended depth. The WEC systems were listed according to their rated capacity and following this criterion they can be grouped in two categories: a) nominal power $\geq$2000 kW, including Wave Dragon [26], Pontoon Power Converter [27], Ocean Energy Buoy (OE) [27], Wave Star [27] and AWS (Archimedes Wave Swing) [28]; b)