Renewable Energy 101 (2017) 244–264

Contents lists available at ScienceDirect

Renewable Energy

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

Assessing the European offshore wind and wave energy resource for combined exploitation

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A R T I C L E I N F O

Article history:
Received 10 February 2016
Received in revised form
25 July 2016
Accepted 5 August 2016

Keywords:
Offshore wind energy
Wave energy
Deep offshore
Combined exploitation

A B S T R A C T

The main concern when utilizing renewable energy resources is their intermittency and variability. One way to deal with this shortcoming is to harvest energy from complementary sources. In this study, wind and wave energy were selected as such and further analyzed in terms of availability, variability, coherence, correlation and potential impact from extreme values. This resource characterization was performed in different timescales, during a 10-year period, using high resolution numerical modeling systems. Based on the results of this analysis, the most suitable areas for combined exploitation were identified and the possible merits from this synergy were pin-pointed and discussed. It was indicated that the most suitable areas for combined use are the western offshore areas of Europe. The wind and wave fields in these open sea areas reveal the lowest correlation in the examined field in contrast to those located in semi-enclosed and enclosed basins that exhibit the highest ones. The joint exploitation in the former regions gives a less variable power output with considerable fewer hours of zero production. Moreover, the suitable energy conversion system for a specific area is strongly dependent on the local characteristics of the available resource.

1. Introduction

Europe has the leading role in the marine power utilization. It accounts for more than 90% of the world's installed offshore wind capacity, while setting targets to cover the 4% of the electrical demand until 2020. The near-shore (less than 50 m) wind power capacity has already reached GWs levels. As the demand for renewables is rising, suitable near-shore sites become sparse, driving the technology to go to higher depths (>50 m). Moreover, deep sea areas like the Mediterranean Sea, the Norwegian coasts or the Atlantic coasts of Europe are experiencing high offshore wind resource that cannot be exploited by the current technology. New offshore designs are to be developed to harness the large wind power potential of the deep offshore environment. For this reason, industry is moving from fixed foundations to floating substructure technology, following the standards of the mature oil and gas industry. However, deep offshore technology is at an early stage of development, facing great challenges especially due to the high design, installation and maintenance expenses.

To compensate with such high costs, potential synergies among complementary resources can provide suitable solutions. In particular, joint exploitation of offshore wind and wave energy is able to increase the energy yield per square meter and at the same time to reduce the variability and the hours of zero production, in areas where the two resources have low correlation. Furthermore, it can lower the operational and maintenance costs, since the two will share common installations [1,2]. Considering now an efficient layout of wave energy converters (WEC's) inside a wind farm, the local wave climate will be modified, providing a sheltered environment for operation and maintenance. The latter can enlarge the accessibility weather windows and protect the wind turbines (WT) from heavy wave loads during storm conditions [3].

In order to optimally harvest the power from wind and waves there is a need for detailed resource characterization that takes into consideration the diversity of the two resources. A number of studies have assessed the wind and wave power potential, independently, either globally [4,5] or at specific sites [6,7]. Several authors used measurements, in-situ or satellite data, solely or along

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http://dx.doi.org/10.1016/j.renene.2016.08.010
0960-1481/

with numerical model outputs [8–12] while others utilized only the results from numerical models for the same purpose [13–15]. Furthermore, data from large hindcast projects performed by well-known operational centers like ECMWF, NCEP etc. have been also widely used to perform such kind of analysis [16–20]. These datasets have the advantage of a wide spatial and long temporal coverage and the disadvantage of a rather coarse resolution. Despite the latter they have been proven useful basically for providing the basis for statistical [21] or dynamical downscaling [7,22–24].

When it comes to combined resource analysis little has been done. Combined exploitation is a rather recent topic and thus few studies have been performed. The vast majority of them worked on a joint wind/wave power analysis at specific locations, either at test sites or at locations where measurements were available [1,3,25–28]. However, most of the research toward this direction has been performed in the framework of EU funded projects that aimed to identify possible synergies for deep offshore resource exploitation [29–34].

In this study, an attempt was made to perform such kind of analysis for the entire offshore area of Europe, using a high resolution wind and wave dataset. More specifically the MARINA database was used [30,31]. This database has been produced in the framework of the MARINA Platform project, using the results of atmospheric/wave modeling hindcast simulations, for a period of ten years (2001–2010). It provides co-located, high resolution information for the main met-ocean parameters and thus was selected for the combined resource characterization. It has been previously used and evaluated for its accuracy, in several studies [2,35–38]. In this work further analysis is performed and the main objectives are:

- To identify the main features of the available offshore wind and wave energy resource of Europe.
- Based on these, to result in favorable locations for combined energy exploitation.
- To evaluate the possible benefits of the combined exploitation on the final power output, in terms of availability and variability.

This paper is organized in the following five sections. In Section 2 a short description of the main climatological characteristics of the offshore areas of Europe is presented. The methodology adopted for the assessment of the wind and wave power resource is presented in Section 3 and the main results of the analysis are presented in Section 4. Finally in Section 5 a brief discussion summarizes the main findings.

2. Study area and prevailing weather patterns

This study is focused on the resource characterization of the deep offshore areas of Europe. The region can be divided in three sub-areas: The North and Baltic Sea, the European coastline that is exposed to the Atlantic Ocean and finally the Mediterranean and the Black Sea. These areas reveal different physiographic and weather characteristics that influence the renewable resources.

Europe is located in the mid-latitudes and thus is characterized by intense atmospheric activity. The western offshore areas of Europe are exposed to the Atlantic Ocean. These areas are strongly influenced by the extra and in some occasions post-tropical cyclones and polar lows that are generated along the Polar and the Arctic front respectively. Their transition paths are strongly controlled by the phase of the North Atlantic dipole (Azores high and the Icelandic low), following the paths of the prevailing westerlies. The intense storm activity over the Ocean creates strong swells that travel hundreds of kilometers towards the western European coasts, controlling the wave climate of the area [19,39,40].

The northern regions of Europe are bounded by the North and the Baltic Sea. The wind and wave conditions in these semi-enclosed, shallow water basins are also controlled by the passage of cyclonic systems such as extra-tropical cyclones and on some occasion polar lows. Strong cyclonic activity is revealed during the positive phase of the North Atlantic oscillation (NAO) (strong Icelandic low and strong Azores high) that enhances and shifts the westerly zonal flow and the cyclones towards the area. The sea wave conditions for both the Baltic and the North Sea can be considered as wind-driven due the limited fetch of the basin.

The closed, deep water, Mediterranean Sea is the southernmost bound of Europe. It is surrounded by complex mountainous terrain and is divided in several sub-basins with different characteristics (Tyrrhenian, Aegean, Ionian, Adriatic and Levantine Sea). The narrow passages between the mountainous ridges channel the air masses toward the Mediterranean. The weather in the area is also affected by the mid-latitude cyclones that reach the basin especially during the negative phase of the NAO (weak Icelandic low and weak Azores high). Nonetheless, the large majority of cyclones are generated within. They differ from the North Atlantic systems in scale, intensity and duration. The spatial distribution of cyclones reveals a seasonal behavior. The complex terrain of the coastline, the high Sea Surface Temperature (SST) along with the high land surface temperature of the northern coastal areas of Africa form a highly baroclinic region, that provides favoring conditions for the generation of cyclones [41–44]. The main cyclogenetic areas are the Gulf of Genoa, the lee side of the Atlas Mountain and the area near Cyprus. Moreover, the Aegean Sea, the Ionian Sea, the Gulf of Syrtis, the Iberian Peninsula and the sea area of Algeria can be considered as secondary cyclogenetic areas.

3. Methodology

To identify suitable locations for the joint exploitation of wind and wave energy resource and to further evaluate the impact of this combined use on the variability of the final aggregate output, a detailed resource and site assessment was performed over the offshore areas of Europe.

In particular, the two energy resources were analyzed in terms of availability, variability, potential impact from extremes, coherence and correlation. The availability, the coherence and the variability were assessed based on the mean and standard deviation values. These were further quantified and evaluated regarding the spatiotemporal variability in seasonal and yearly scales. The possible impact from extremes was estimated, during the decade, using the higher moments of the dataset, namely skewness and kurtosis. The latter give information about the symmetry of the dataset and the infrequent extreme deviations from the mean.

The data used for the aforementioned analysis are the product of hindcast numerical simulations. This dataset was produced in the framework of the FP7 MARINA Platform project [30,31] and provides information for the main met-ocean parameters needed for a detailed resource assessment.

3.1. MARINA platform database

The hindcast dataset used for this study provides information for the entire European coastline, for the period between 2001 and 2010, with an hourly time frequency and a spatial resolution of 5 km (Fig. 1). The modeling system used to construct the dataset consists of the limited area atmospheric model SKIRON [45–47] and the 3rd generation wave model WAM [48,49]. The atmospheric/wave modeling system has been utilized and evaluated in a