Energy 97 (2016) 411–423

Contents lists available at ScienceDirect

Energy

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

The expected efficiency and coastal impact of a hybrid energy farm operating in the Portuguese nearshore

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ARTICLE INFO

Article history:
Received 5 September 2015
Received in revised form
31 December 2015
Accepted 2 January 2016
Available online xxx

Keywords:
Hybrid farm
Portuguese nearshore
SWAN (Simulating WAves Nearshore)
Waves
Coastal impact

ABSTRACT

The objective of the present work is to provide a comprehensive picture concerning the expected efficiency and coastal impact that would result from the implementation of a hybrid wind-wave project in the northern part of the Portuguese nearshore. As regards the wind, the data considered are from the European Centre for Medium-range Weather Forecast and covers the 20-year interval 1995–2014. For the wave conditions, data provided by in situ buoy measurements corresponding to the 15-year time interval (1994–2010) have been processed and analyzed. As a first step, the potential of the wind and wave resources was assessed in terms of their seasonal variations. This was further completed with results concerning the expected power output and the efficiency of some state of the art wind and wave converters. The second part of the proposed work is focused on an evaluation of the down-wave effect induced by a hybrid wind-wave farm. Following the results of the present work, it can be noticed that the wave farm can assure a beneficial sheltering effect to the wind farm fact that should lead to an increase of efficiency of the wind energy extraction.

1. Introduction

In order to improve the consistency of the electrical power output generated from the renewable sources, there is an increasing trend to combine multiple natural resources in so called hybrid energy projects. On a small scale the benefits of such projects are obvious, since they improve the life quality of the people living in isolated areas by providing a reliable source of electricity, it is expected to improve their education and to reduce poverty [1,2]. Larger capacity projects can benefit in this way from the full potential of the natural resources, becoming more competitive with the oil industry, since they will reduce the dependency from the fossil fuels products. Multiple combinations can be designed by considering proven technological systems related to: PV (photovoltaic), solar hot water, wind, geothermal or hydropower [3–5].

At an European level by the end of 2013 the wind industry reported a cumulative capacity of 117,741 MW, a value which is similar with the solar sector where a market of 79,623 MWp (megawatts peak) operates for the PV-systems and of 31,389 MWth (thermal megawatts) for the thermal industry, more important outcomes being reported in France, Germany, Austria, Italy and Portugal, respectively [6]. Although at this moment Europe presents a relatively downward trend in terms of renewable projects, this still remains an attractive region since it is defined by a large portfolio of natural resources and a sustainable energy policy [7–9].

The wind and wave conditions are interconnected, their potential being accurately identified on a global scale, especially in the vicinity of the coastal environment [10–13]. The wind presents a more consistent energy potential than on the land, which cumulated with the large marine areas create all the conditions required to develop larger energy projects. As a drawback the intermittency of the wind resources and the weather conditions on the sea can be mentioned. These may impose some restrictions on the building and maintenance of the offshore wind parks. The wave conditions are less intermittent since they are generated by storms in the offshore areas, the beach areas facing the ocean environments encountering swells with an increased energy potential coming from various directions. The disadvantages are related to the storm conditions, but these events can be accurately identified throughout numerical simulations which will allow the WECs (Wave Energy Converters) to be shut down in order to prevent their failure [14,15].

The benefits of a hybrid wind-wave project are coming from the fact that for a single location the energy is collected from two

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http://dx.doi.org/10.1016/j.energy.2016.01.002
0360-5442/

different natural resources, being possible to use the same infrastructure which will allow a smooth development of each project and a significant attenuation of the initial investments [16]. On the other hand, the wave energy farm can assure a beneficial sheltering effect to the wind turbines, fact that should lead to an increase of efficiency of the wind energy extraction. Moreover, there are increasing voices which consider that projects like this could provide a more efficient coastal protection [17–22].

Portugal is one of the most dynamic countries in terms of development marine energy projects. This is not surprising if we take into account the fact that Portugal has a long continental coast and it has a large stretch of ocean to the west. If we discuss about the wind energy, the WindFloat project might be considered among the most ambitious. It started in 2011 with a single Vestas 2.0 MW wind turbine, located at approximately 5 km from the coast at an average water depth of 45 m. This is a grid connected project located in the vicinity of the Aguçadoura district (northern Portugal) which is predicted to reach at least a 150 MW installed capacity [23]. Coincidence or not, in the same location, during 2008 the world's first wave farm was installed, which was defined by a capacity of 2.25 MW provided by three Pelamis systems. Nevertheless, during the strong wave conditions that occurred in November 2008, the Pelamis machines were brought back to the Leixões harbor due to a technical problem with some of the bearings for which a solution has been found. However, according to Pelamis those machines (version P1) were sub-optimal and Pelamis company focused its efforts on the next generation machines (version P2) that were further tested in Scotland. That is why the project had to be shut-down.

Another important pilot zone is located in the central area of Portugal, near the city São Pedro de Moel, where the entire area of 320 km^2 has facilities to connect any wave project to the transmission grid, the investors benefiting from a special tariff of the wave energy, which starts from 260 Euro for the first 20 MW and gradually decreases for additional installed systems [24]. Following these opportunities, several projects were implemented over time, such as the Pico plant (Azores in 2006) or WAVEROLLER (Peniche in 2014), while most of the activities are focused on the research activity which involve new concept development, testing WECs or environmental issues, respectively [25].

Motivated by these aspects, the present work aims to identify the efficiency and the expected impact of a hybrid wind-wave project operating in the coastal environment north to the city of Porto, at approximately 30 km south of the Aguçadoura site.

2. Methods and materials

2.1. Target area and computational domain

Fig. 1 presents the target area considered for evaluations. In the left side of the figure we can notice that the Lexioes region is located in the northern part of Portugal continental, considering as a reference point the city of Porto. A particularity of this area is that it includes also a harbor, which could represent an advantage for the development and maintenance of a renewable energy project. The shoreline orientation is in general defined by the north and south-east directions. At this point it has to be also highlighted that due to the general wave propagation patterns and to the particular geographical configuration of the target area, it is expected that the hybrid farm would not affect in any way the navigation and the operations at Leixoes harbor, located in the south of the target area. On the other hand, the proximity to the city of Matosinhos represents a real advantage in relationship with the grid connection.

The wave conditions and the performances of the WECs will be identified considering the in situ measurements carried out at the Leixoes buoy (41°2′N, 9°09′W), which is located in the close vicinity of the target area, while the wind resources have been identified by using the ECMWF (European Centre for Medium-range Weather Forecast) data, in a reference point located inside the target area. More details about the two datasets will be provided in the next section.

The SWAN (Simulating WAves Nearshore) computational domain is indicated in Fig. 2, this area being defined by a rectangle with equal sides of 6 km. A maximum water depth of 35 m is reported in the offshore area while in the central part, the 15–20 m values are more common for the water depth. Two distinct parts compose the hybrid farm setup, each one being defined as obstacles with particular absorptions properties. In Fig. 2 and next, the wave farm is represented with a dotted line which has a length of 1.8 km, while in terms of the absorption properties two main scenarios were considered for evaluation: a) moderate absorption → $C_{tr} = 0.8$; $C_r = 0.05$; b) high absorption → $C_{tr} = 0.6$; $C_r = 0.08$, where with C_{tr} and C_r the transmission and reflection coefficients were denoted. The setup is completed with the wind farm which was designed to include nine turbine platforms, parallel to the coastline and grouped on two lines, each one having a length of 60 m, which is similar with the dimension of the WindFloat platform [26]. Since the recommended distance between the systems in a farm is considered to be around 3 to 5 rotor diameters, for the present work the lowest value was considered in order to highlight the maximum influence of the turbines on the local wave fields [27]. The wind turbines were defined as obstacles, considering the following transmission/reflection values: $C_{tr} = 0.9$; $C_r = 0.05$.

Three reference lines (L1, L2 and L3) crossing the hybrid farm were defined, in order to assess the transformation of the waves passing through the farm and approaching the shoreline. The specific depth (in meters) along each line is also indicated in Fig. 2, with the mention that each line was chosen to intersect at least one wind turbine in order to put in evidence also its influence. Besides this, in the vicinity of the coastline six reference points (P1–P6) were selected. This will allow the evaluation of the nearshore wave characteristics variations induced by the presence of the hybrid farm.

2.2. SWAN model and ECMWF dataset

Since waves are composed from irregular heights and periods which are caused by the irregular winds it is usually difficult to describe the sea state in a deterministic way, so therefore the sea surface elevation can be more accurately expressed as a Gaussian process. Following this approach, a reliable estimation of the sea surface variation in the coastal areas can be obtained by using third-generation wave models. SWAN is one of these models [28], being capable to determine the evolution of the action density $N(\vec{x}, t; \sigma, \theta)$ in the geographical ($\vec{x}$) and spectral spaces as also in time (t). Thus the governing equation in the spectral models is the action balance equation, which can be expressed as [29]:

$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}} \cdot \left[\left(\vec{c}_g + \vec{U} \right) N \right] + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (1)$$

where, the kinematic part of the equation (left side) includes the following terms: the first term gives the time variation of the action density, the second term accounts for the propagation of wave energy in the two dimensional (geographical) space, $\vec{c}_g = \partial\sigma/\partial\vec{k}$ representing the group velocity; the third term represents the shifting effect of the radian frequency by taking into account the variations in depth/currents; the fourth term is related to the depth-induced and current-induced refraction, with the mention