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Towards an optimum design of wave energy converter arrays through an integrated approach of life cycle performance and operational capacity

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HIGHLIGHTS

- The performance of WEC arrays is evaluated during their whole life-cycle.
- The applied methodology optimises the design of WEC arrays.
- Downscaling techniques are applied to reduce computational costs.
- Analysis of the main variables related with maintenance and operation.
- Different WEC array geometries are tested in the Gulf of Cádiz.

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ABSTRACT

Over the last few decades, several efforts have been made to develop an alternative and sustainable energy source from wind waves. To achieve financial sustainability of this technology, most of the research has focused on analyzing facilities composed of several wave energy converters (WECs) arrays instead of isolated ones. Although the interaction between devices and its implications on the performance of the facilities have been studied previously, these works considered only certain combinations of sea states, limiting the applicability of the results. This work applies a new methodology based on statistical methods to assess the performance of different WEC array distributions during their entire life-cycle in an efficient way, using downscaling techniques and advanced numerical modeling to propagate the wave climate. The results obtained during the hindcasting life-cycle are used to analyze the maintenance and operation capabilities of the different alternatives of arrays defined for the WEC facility. The interactions between devices and their efficiency considering the associated impact are also quantified. The assessment of these efficiencies during the complete life-cycle of the devices is highly valuable tool for promoters and coastal managers to evaluate different WEC array alternatives. The entire process was applied to a hypothetical array location in the Gulf of Cádiz (southwestern Spain), where three different array distributions were defined. The results show that the distance between WECs is a key parameter that controls the potential energy production, the efficiency of the facility and the interactions between several devices.

1. Introduction

During recent years, the development of non-conventional renewable energy technologies has received increasing attention due to the environmental problems derived from the use of fossil fuels. Among these non-conventional sources, marine energy resources can be stored in the form of thermal, kinetic, chemical and biological energy [1]. Accordingly, many recent works have focused on these types of sources, especially on hydro-kinetic energy extraction. Two main technologies have been developed: (1) the extraction of energy from tidal currents using Tidal Energy Converters (TECs; [2]) and (2) the extraction of energy from waves by wave energy converters (WECs; [3]).

WECs generate electricity from the kinetic energy of waves through different physical processes, such as wave overtopping, wave impact or wave oscillation [4]. Depending on their specific characteristics, these devices can be fixed not only at maritime infrastructures but also in nearshore or offshore bathymetric zones and usually have dimensions ranging from tens to hundreds of meters [4]. To optimize the economic viability of this wave energy resource, the devices are frequently not installed isolated but in arrays or farms of many units [5]. However,

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these arrays must be carefully designed to avoid inefficient interactions between the devices due to the modifications of the wave field that they may generate [6].

Numerous studies have focused on the interactions among nearby devices. Initial works analyzed very simple array geometries forced by unidirectional regular waves [7,8]. Later, research interest was focused on more complex design parameters: Babarit [9] analyzed the interaction between two WECs and the influence of the separation between them, whereas Cruz et al. [10] used regular and irregular waves to analyze the interactions in the array layout and the control strategy of the facility. Furthermore, Borgarino et al. [11] presented a study on the interaction between WECs in arrays of 9–25 devices within a yearly scale. de Andrés et al. [12] addressed the optimum array configurations, in terms of power production, for different wave climates around the globe. Engstrom et al. [13] and Goteman et al. [14] analyzed fluctuations in the power availability of different arrays configurations, minimizing the power variance for some wave conditions and array geometries. More recently, Bozzi et al. [15] assessed the performance of different WEC array geometries along the Italian offshore platform using some combinations of real sea states.

Despite the importance to potential investors, these previous studies only considered certain wave conditions without focusing on the life-cycle performance of the arrays. The life-cycle assessments of WECs and WEC arrays were focused on their environmental and economic impacts [16,17] at different stages of the facilities (i.e., installation, use and dismantling) and energy productions that were roughly estimated [18] using only mean values of the resource rather than obtaining the complete time series during the life-cycle on a high temporal resolution basis. More exhaustive analyses were performed for energy assessments at large scale areas, based on hindcasted wave climate time series. These analyses were performed for different durations, ranging from a few years [19] to more than 60 years [20]. For these analyses, different models such as WAVEWATCH [21] or MIKE21 [22] were employed. However, these studies do not consider the presence of WECs and their influence on the local wave field. To the authors knowledge, López-Ruiz et al. [23] was the first study where the energy resource was assessed and forecasted for the complete life-cycle of isolated WECs. More recently, Bailey et al. [24] presented a stochastic model for predicting WEC array power time series, applicable only for arrays of independent WECs.

Although significant advances have been achieved during the last decade, a unified framework to evaluate the performance and operational capabilities of different alternatives of WEC arrays during their complete life-cycle is still lacking. As described previously, some works analyzed only certain combinations of wave climates, whereas others were focused only on the performance of the facilities. Furthermore, the operational and maintenance capabilities were obtained for large-scale analyses with low spatial and temporal resolutions and without considering the interaction between WECs and hence the local wave conditions [25,26] which critically affects the results. This limits the applicability for decision-makers, who usually must make important investments in a technology where the commercial margins are narrow.

The main objective of this work is to present the first unified methodology for assessing the potential life-cycle performance of different geometrical configurations of WEC arrays using a hindcasting wave climate and statistical tools to reduce the computational costs. The methodology obtains not only the energy production of the arrays during their life-time but also their operational and maintenance capabilities, providing a unified framework to evaluate WEC array alternatives. The efficiency of the alternatives is also obtained in terms of the occupied surface and length of the wave front affected by the WECs. These aspects were not analyzed previously using neither experimental nor numerical methods, neglecting the visual, navigational and environmental impact of the arrays. The methodology presented throughout this paper is the first to allow the assessment of these efficiencies during the complete life-cycle of the devices. It can assist promoters and coastal managers during the evaluation of different WEC array alternatives, allowing a more accurate assessment of both the life-cycle performance and maintenance aspects.

The methodology, which will be described throughout the manuscript, can be divided into two main stages: (1) the definition of the WEC array configuration and (2) the evaluation of its performance using a numerical model. Furthermore, cutting-edge statistical methods are applied to obtain the wave energy potential for every individual WEC during its life-cycle with a minimum computational cost. The methodology is used to evaluate 9 different array configurations consisting of 9 WEC units in the southwestern coast of Spain. The results are obtained for a set of 25-year hindcast wave data. The different alternatives are evaluated in terms of not only their energy production but also their environmental impact (i.e., occupied surface) as well as operational and maintenance aspects.

The methodology employed in this work applies not only to any type of WEC array (regardless of the particular device employed) but also to any other renewable energy resource that is dependent on atmospheric forces (i.e., wind energy). It was developed to be applied straightforwardly to real applications, as cutting-edge statistical techniques are used in such a way that they can be directly applied by investors and decision-makers to optimize the design of WEC arrays, reducing the gap between research, development and implementation.

2. Study site

The southwestern area of the Gulf of Cádiz is one of the few locations along the southern coast of Spain where it is feasible to install a WEC array due to its wide continental shelf (30 km), relatively low depths and mild slopes [27], with the shelf-break at approximately 120 m water depth (Fig. 1a and b). In addition, there is a strong wave energy potential in this area [28]. These characteristics enhance the feasibility of exploiting the wave energy resource according to the guidelines of the Kyoto protocol and the European Union and Spanish energy politics [29]. In this work, the WEC arrays were placed at the widest part of the inner continental shelf, close to Trafalgar Cape, so that the arrays operate in intermediate depths (approximately 34 m) but at a considerable distance from the coast (≃ 10 km). This location is feasible in terms of economical exploitation [30,31], and it minimizes the environmental impact of the facility since it may provoke minimum disturbances on sediment transport both at the study site and at the shore.

The area is a mesotidal and swell-dominated coastal environment. The astronomical tide is semi-diurnal with tidal ranges between 1.2 m and 3.8 m [27]. Wave data from SIMAR point 5034009 indicate that the prevailing incoming wave directions are west and west-northwest (Fig. 1c). The 50%, 90% and 99% exceedance significant wave heights (H_s) in deep water are 1.1 m, 2.2 m and 4.0 m, respectively. During extreme storms, maximum significant wave heights typically exceed 3.5 m.

3. Methodology

The methodology applied to hindcast the performance of different WEC arrays geometries in the study site is described in the following sections. Furthermore, we present the tools used to analyze the results, including the procedure to evaluate the relative impact of the different array layouts.

3.1. Wave climate

The main objective of this work is to evaluate the performance of WEC arrays during their life-cycle, which is usually considered to be 25 years [32,33]. Hence, we gathered a wave dataset spanning 25 years, obtained from the hindcast database of Puertos del Estado (Spanish Ministry of Public Works).