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Wave energy resource variation off the west coast of Ireland and its impact on realistic wave energy converters' power absorption

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HIGHLIGHTS

- Historical wave trends are studied via ECMWF's reanalyses over the 20th century.
- ERA20 is calibrated via quantile-matching and validated against buoy measurements.
- The wave energy resource increases over 40% off the west coast of Ireland.
- A 30% surplus of AMPP is observed for different WECs due to resource variations.
- Extreme events occurrence doubled, doubling the time WECs spend in survival mode.

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ABSTRACT

Wave energy converters are specifically designed to extract the maximum energy from a given location. To that end, wave data statistics based on past measures at the given location are commonly used, neglecting any possible future wave trend. This paper studies the variations of the wave energy resource off the west coast of Ireland over the 20th century via the atmospheric reanalyses created by the *European Centre for Medium-Range Weather Forecasts*. In particular, the European Re-Analysis ERA20 is calibrated via quantile-matching against the new European Re-Analysis ERA-Interim for the period 1979–2010. In addition, the calibrated ERA20 reanalysis is validated against buoy measurements in the area of interest. Results show a significant increase of the wave energy resource along the last century (an increase of over 40%), for which the largest increase is observed within the last 20 years (an increase of 18% between 1980 and 2000). The paper shows that these variations considerably affect the power absorption of realistic devices, showing a power surplus of up to 15% within the lifespan of a wave energy converter. Finally, an increase of extreme events over the last century is also observed, highlighting its impact on power production due to the need of wave energy converters to switch into survival mode during extreme events.

1. Introduction

In the way to reduce greenhouse emissions and mitigate the effects of climate change, renewable energy systems play a crucial role. Renewable energies already cover almost 20% of the total final energy consumption in the world, where hydropower, biomass, solar and wind energy are currently the main contributors to the national electricity grids all over the world [1]. However, other renewable energy sources, such as wave energy, have the potential to also contribute to the energy mix. The worldwide potential of wave energy is estimated to be around 32,000 TWh/year [2], which suggests that wave energy can be a good candidate to increase the weight of renewable energies in the energy mix.

Despite the enormous power stored in ocean waves, the harsh environment in which wave energy converters (WECs) need to operate makes the energy production from ocean waves complex and costly [3]. In addition, several different WEC concepts have been suggested by researchers and developers [4], but none of the concepts has

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demonstrated commercial viability yet.

Once commercial viability is achieved for any WEC concept, an accurate characterisation of the resource at the location where the WEC, or WEC farm, is to be deployed will be vital. The wave energy resource of a specific location is often presented in scatter diagrams that are generated using only past measurements [5]. These scatter diagrams are characterised by two main variables: peak period (T_p) and significant wave height (H_s). However, only considering past data neglects any possible variation of the resource in the period where the WEC is supposed to operate, meaning that WECs designed using these scatter diagrams are designed for the past resource, while deployed in the future resource.

Therefore, wave resource variations must be considered to accurately design WECs. Following the recommendations by the World Meteorological Organization [6,7], reliable estimations of climate variables require at least 30 years of data. This data may be obtained by means of different techniques, such as buoy measurements [8], observations from ships [9,10], satellite altimeter [11,12] or models and reanalysis datasets [13–20]. The latter method, i.e. reanalysis datasets, is used in the present study, using atmospheric reanalyses of the *European Centre for Medium-Range Weather Forecasts* (ECMWF). Among the different options, the European Re-Analysis *ERA20C* is used, calibrated against the *ERA-Interim* reanalysis via the empirical quantile-matching technique.

1.1. Literature review

Reanalysis datasets are employed for different applications in the literature. For example, a global wave energy resource study is carried out in [18,20] using a 40-year reanalysis *ERA40*, which is the previous version of the reanalysis based on the Wave Modeling Project (WAM) *ERA-Interim-WAM*. Both [18,20], are large-scale studies focused on worldwide climate patterns, where [18] calculates wave trends by means of linear regression, while [20] uses a method based on swell index and the propagation characteristics of swell energy. Similarly, Ref. [19] presents a global study of the wave energy resource.

Similar methods are also used to estimate wave height trends of the North Atlantic Ocean in [17], where the *ERA20C* reanalysis is used. In this particular case, wave height trends are studied in relation to wind speed variations. However, Ref. [17] uses results obtained from *ERA20C* without calibration, since the aim of the study is analysing the effect of climate change in wave height trends. Apart from reanalysis datasets, other techniques have widely been used to document wave height variations all over the world, where Ireland is a particularly well reported area due to the very energetic waves and high variability. For example, Ref. [12] studies wave height variations off the west coast of Ireland between 1985 and 2008 using satellite data and shows an annual increase of approximately 0.25%, which indicates a trend of more than 5 cm/decade based on an average 3 m-wave. In situ observations near Ireland have also been used to document wave height variations. Bouws et al. [21] uses historical hand-drawn charts of the south of England and shows a positive trend in wave height of 24 cm/decade over the period 1960–1985. In addition, Refs. [9,10,22] use centennial time series of visually observed waves from ship routes to report wave height trends in the North Atlantic Ocean, demonstrating positive trends for H_s of up to 14 cm/decade. Based on these visual observations, Gulev created a European map of wave height trends, indicating a trend of approximately 5 cm/decade off the west coast of Ireland. This wave height trend is consistent with the results presented in [12] and in the present paper.

The vast majority of wave trend studies, as described in the above paragraph, focus on wave height trends, while wave period trends are often neglected. Presumably, the main reason to neglect wave period trends is that wave period variations are of little interest for other research areas or industries than wave energy, which is still an immature industry. Some very recent research works study wave period variations by means of statistical models similar to those used in the present paper: wave period trends in the Bay of Bengal are analysed in [23] combining satellite altimeter data with ERA-Interim and ERA-20 reanalyses and the evolution of peak periods and wave heights is studied all over the world in [24]. However, wave period trends are analysed for coastal impact assessment in [23,24], where wave climate variations are rather projected towards the future (1979–2100), instead of studying historical records of the last century, as in the present paper. Although [24] is a global study, more localised areas, such as Southern Australia and Western South America, are also selected for finer studies. Unfortunately, these more localised areas are far from the area of study evaluated in the present paper, so results cannot be compared as with wave height trends.

Other potential methods for the study of wave period and height trends include satellite and remote sensing data. Apart from altimetric data directly related to the significant wave height, satellites like TOPEX, ENVISAT or Sentinel also record a second parameter, the backscatter coefficient (σ_0) of the electromagnetic signal, which, in combination with the wave height, allows for the estimation of the mean wave period [25–28]. However, wave period observations by means of satellite and remote sensor have been considered unreliable until 2005 [25]. In addition, the vast majority of the studies in the literature analyse the wave power density from a pure climatological perspective, only analysing the pure resource. Therefore, no special attention has been paid to period trends.

Nonetheless, wave period variations are crucial to accurately evaluate the impact of wave energy resource variations on WEC's power absorption. The only study that includes wave height and period variations, to the authors' knowledge, is a preliminary study carried out in the Bay of Biscay by the same authors [29], where significant increment of the resource and absorbed power are observed over the 20th century. However, the impact of wave resource variations on WEC's in [29] is analysed using a generic WEC with a spherical geometry and a excessively simplified WEC model.

Other studies that analyse the wave energy resource at different points all over the world using similar reanalyses or mesoscale models, consider wave heights, wave periods and wave directionality [30,31]. However, these studies are based on hindcast data that covers at most two times the lifespan of a WEC (approximately 20 years). In addition, the aim of these studies is the assessment of the resource at specific locations with high spatio-temporal resolution, which is performed via the wave energy transformation model SWAN using calibrated source-term parameters, and, as a consequence, only seasonal or inter-annual variabilities are analysed.

The present paper presents a novel methodology to analyse the historical evolution of the wave energy resource and evaluates resource variations off the west coast of Ireland over the whole 20th century for the first time. The insight provided by the analysis of the historical evolution of the wave resource along a whole century is significantly more valuable to understand historical wave trends and, eventually, the future resource and its impact on the power production of WECs. Therefore, this paper focuses on wave period, wave height and wave energy flux (WEF) variations over the 20th century, similarly to [29]. However, the present paper includes substantial improvements that provide more consistent results. Firstly, the methodology to assess wave energy resource variations is validated in a completely different location: The Bay of Biscay studied in [29] is a rather closed area where the wave resource is mild (about 20 kW/m), while the west coast of Ireland analysed in the present paper is open to the Atlantic Ocean and the wave resource is considerably higher (60 kW/m). Second, the impact of wave energy resource variations on WECs' power absorption is studied using two fundamentally different WECs based on full-scale real prototypes. Third, a more accurate hydrodynamic model that considers time-domain dynamics, multiple degrees of freedom (DoFs) and constraints is employed. Finally, variations of extreme events and the consequences of turning the WEC into the survivability mode during