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Wave energy characterization and assessment in the U.S. Gulf of Mexico, East and West Coasts with Energy Event concept

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ABSTRACT

Wave energy is one of the most concentrated ocean renewable energy resources. Although wave energy has been studied extensively for more than four decades, there is no large commercial installation for wave energy production or a consensus framework on how to exploit this resource. Wave energy is a complex resource that directly depends on two meteorological parameters, which produced significant fluctuations of wave energy in both temporal and spatial criteria. This paper presents a new concept called Energy Event, to analyze meteorological data generated by WaveWatch III over 36 years in the U.S. to characterize and assess wave energy behavior using the peak-over-threshold methodology. This methodology used extreme statistics, segmented the wave energy with different thresholds, and assessed wave energy production on a temporal and spatial framework. Three areas were studied in this paper, including the Gulf of Mexico, the East and West U.S. Coasts. The results indicated that wave energy behaved as a two-state energy system with each state having independent characteristics. The main difference among the three studied areas was the constant baseline of wave power density, with the West Coast having the highest constant baseline and the Gulf of Mexico having the lowest baseline.

1. Introduction

The variability on the supply and prices of hydrocarbons due to unpredictable factors and the emission of pollutants and greenhouse gases from traditional fossil fuels make the use of non-renewable resources unsustainable [1–3]. Additionally, global climate change has been considered as one of the most pressing challenges for human development and renewable energy has been recognized as one of the most promising avenues to ameliorate this danger. Furthermore, the continuous improvement on wind and solar energy harvesting over the past five decades has reached a point where these resources are economically competitive with other traditional fossil fuels. It is expected that future improvements will even make them competitive with natural gas [1,2,4].

Ocean renewable energy resources can provide current and future energy needs. Among these resources, wave energy is one of the most concentrated and persistent energy resources, and has been considered for electricity generation with great interest for more than four decades. Large human populations living near the coasts and the enormous economic activities on the oceans make the harvesting of energy from the waves very attractive [5–9]. However, the complexity of wave resources has made wave energy development very challenging. After decades of research, there is still no large commercial wave energy installation and no consensus on the equipment design required for its exploitation. A large number of prototypes, based on various principles, have been proposed and currently continue being tested to find the best option for wave energy harvesting [1,5–9].

The main factor influencing wave energy harvesting is the available wave resource. However, previous research has determined that this resource fluctuates dramatically on spatial and temporal criteria. Some regions show very large wave energy density overall, but it may show significant temporal variability when zooming into individual areas. On the other hand, low overall wave energy regions may have promising areas with relatively high wave density that have low temporal variability and are close to consumption areas. Furthermore, some researchers have indicated that high wave energy regions frequently produce extremely large

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waves that make the survival of any device more precarious, speculating that some low producing areas could be better suited for wave energy harvesting [5,6,8,10,11]. Regions with low wave energy density, such as the Mediterranean and the Caspian Sea, have been investigated in previous research indicating that they could produce adequate level of wave energy to supply local demand [8,10–13]. The Gulf of Mexico (GoM) has also been classified by previous research as a low producing area [14,15], which comprises more than 1,500,000 km^2 [16] assuming uniformity of wave energy generation over the entire GoM area. A large electricity consumer base exists in close proximity of the GoM, with important urban and industrial settings and more than 4000 oil platforms that require energy supply. Furthermore, previous studies have indicated that the GoM has ample capacity of wave energy with an annual available wave resource of 83 TWh on the outer shelf and 60 TWh on the inner shelf [14–21]. Therefore, the GoM presents a compelling case for studying wave energy harvesting.

Previous research on the assessment and characterization of wave energy has relied on methodologies that lack the capability of including its high temporal and spatial variability [2–7]. They rely on assessing wave energy using statistical indicators (such as average or variance) [22,23] and representing results on the form of wave power roses (to evaluate frequency and direction) [4,24], graphical representations (scatter plots, line graphs or histograms) [25] and static maps (direction vectors, data points or isolines representations) [6,12]. However, since wave energy does not behave linearly due to the fact that the significant wave height (Hs) is squared when calculating wave power, these statistical indicators and its static representation lead to incomplete wave energy assessments and characterizations [3,26,27]. The lack of adequate assessment and characterization of wave energy has caused a significant delay on wave energy development and the deployment of WECs that might underperform or be damaged by extreme waves that have not been completely characterized [28–34].

Therefore, this paper focused on the development of a new methodology to assess and characterize the spatial and temporal variability of wave energy in the U.S., addressing the complexity of the waves while applying a new Energy Event concept to gain a better understanding of wave energy behavior. Peak-over-threshold method from extreme statistics was applied to segment wave energy with different thresholds. Wave energy behavior on a temporal and spatial framework was investigated to understand how to better harvest wave energy while reducing the risk of damaging the wave energy converters (WECs). The methodology presented in this paper considers the high spatial and temporal variability of wave energy into analysis to overcome those limitations discussed above, providing a more completed wave energy assessment and characterization. Additionally, the use of the long-term data set allows to cover the variability caused by inter-year variations of the wave energy resource and to validate the methodology when considering the high temporal variability factor. In this paper, analysis was performed on three regions of the U.S., including the GoM, the East Coast, and the West Coast. The results of the GoM were discussed in detail followed by comparison results among all three studied areas.

2. Methodology

Wave energy was calculated using 36 years (1979–2015) of meteorological data provided by WaveWatch III system (version 3.14) operated by the National Oceanic and Atmospheric Administration. The data included significant wave height and dominant wave period, every three hours over 36 years in the three studying regions. The data spatial resolution was one sixth longitude by one sixth latitude, which represented the area of an individual location in this paper [35,36]. Wave power density (P) was calculated on kilowatts per meter of wave crest width (kW/m) according to Eq. (1) as indicated in Refs. [18,26,27].

$$P = \frac{\rho g^2}{32\pi} \; T_e H_s^2 \tag{1}$$

where ρ is seawater density (kg/m^3), g is gravity constant (m/sec^2), T_e is energy wave period (sec) and H_s is significant wave height (m).

Since seawater density and gravity are constants, Eq. (1) can be expressed as:

$$P\,(kW/m) = 0.49 \; T_e H_s^2 \; = 0.49 \; \alpha \, T_p H_s^2 \tag{2}$$

Where, T_p is dominant wave period (sec). The equivalency between T_e and T_p is obtained by the application of the wave period conversion factor (α). As the spectral width decreases, the conversion factor increases to one, and it has been considered as 0.86 for a fully developed ocean as indicated in Refs. [10,37]. In this paper, α was considered as 0.9, which is the equivalent of JONSWAP software [37,38] and has been used in the past by different studies [7,10,22,37–41].

A new methodology called Energy Event is proposed that includes the peak-over-threshold concept from extreme statistics and resource segmentation with thresholds. This new method investigated the wave energy behavior on a temporal and spatial framework. Extreme statistics has been used by marine sciences for a long time to assess risk to marine and costal structures exposed to extreme waves. Wave resource complexity is exacerbated by the fact that the cycle of creation, transport and disappearance of wave resources is influenced by a wide variety of factors changing from different locations and even on a time scale. Furthermore, the weight that wave height and wave period have on the wave power output is an important consideration, which has been tackled by previous research with inconclusive results for the harvesting of wave energy [6,10,42,43]. The methodology used in this paper allowed identification and characterization of temporal and spatial trends of wave energy in different areas considering the time and geographical differences.

Three dimensional scatter plots were used to present selected results in this paper, in which latitude, longitude and time were represented as x-axis, y-axis and z-axis, respectively. Each colored data point represented wave energy density present on that time/space location with a color bar indicating the wave energy density level. The 3-D plots showed the significant wave energy changed both over time and space, with several solid objects representing distinctive increases on energy. The gaps between solid objects indicated low wave energy density time periods. The use of 3-D scatter plots of wave energy density identified several and independent wave power densities that increased above certain threshold, which was named as wave Energy Events in this paper. A wave Energy Event is defined as a period of time in which the peak wave energy in a predefined geographical region is above certain threshold. Meanwhile, the periods of time in which the wave energy in a predefined geographical region is below certain threshold are named Breaks. The identification of wave Energy Events and Breaks requires the selection of a threshold, partially adapting the peak-over-threshold methodology, to mark the beginning and the end of the energy event in a predetermined area. Thresholds were determined on kilowatts per meter of wave crest width (kW/m) since the evaluation of the Energy Event is developed based on wave power density. As an example, the wave Energy Events that occurred in January 1979 in the GoM (Fig. 1) clearly shows five solid objects, which have a contour representing the perimeter of the GoM on the x and y axes and with dark blue on its exterior color.