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Integrating ocean wave energy at large-scales: A study of the US Pacific Northwest

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ABSTRACT

This paper assesses operational impacts of large-scale ocean wave energy development in the US Pacific Northwest. High-resolution wave power production and forecasting data is synthesized for wave energy arrays spatially-distributed along the region's coast. Geographic diversification is found to limit the rate at which production variability scales with installed capacity, over timescales ranging from minutes to hours. The reduced variability makes it easier to forecast short-term wave generation accurately. When modeled within the operational structure of the region's primary balancing area authority, large-scale wave energy is found to provide a relatively high capacity value and costs less to integrate than equivalent amounts of wind energy.

1. Introduction

The Pacific Northwest coast of the United States (US) is home to a substantial ocean wave energy resource [1,2]. Regional advocacy groups, established to help develop the region's wave energy resources, target up to 500 MW of capacity installed by 2025 [3]. Developing wave energy at these scales is expected to provide a number of benefits to stakeholders in the region including economic growth, access to low-carbon energy, reduced transmission losses, and generation portfolio diversification [3].

Amidst these opportunities lie potential grid integration challenges. The power produced by ocean wave energy resources is expected to vary unpredictably over timescales ranging from seconds to years [4–10]. Forecasting error translates to unforeseen energy imbalances in power system operational planning. Integration costs derive from holding and operating incremental balancing reserve capacity, and reduce the value of the generated renewable energy [11,12].

The purpose of this paper is to estimate systemic operational impacts of future ocean wave energy development in the US Pacific Northwest. High-resolution wave power production and forecasting data is synthesized for large-scale wave energy arrays spatially-distributed along the region's coast. Incremental reserve capacity requirements needed to integrate the wave energy arrays into the operational system of the region's largest balancing area authority, the Bonneville Power Administration (BPA), are identified. The degree of spatial and temporal detail of the data captures important effects of geographic diversification over multiple scales.

Geographic diversification refers to the location of resources in spatially-distributed regions. The smoothing effect of geographic diversification on power production variability is a well studied phenomenon within the renewable energy integration literature [11–17]. Recent studies indicate that similar benefits are expected when integrating geographically dispersed wave energy resources [5,10,18]. Within the area covered by an array of devices, there is considerable variation in the wave field. This means that the variations in power output from individual converters may average out. Aggregating over regional-scales implies further smoothing, since there is less correlation among wave fronts across long distances.

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Integration into a balancing area containing other uncertainties (e.g., load or other renewable generation) can bring additional benefits; if the variability of each process is relatively uncorrelated, fluctuations can balance out [19,20].

In this paper, we build upon the work of [6,10,19] to provide a comprehensive analysis of geographic diversity and its operational impact on a future ocean wave energy development scenario in the US Pacific Northwest. The paper further analyzes available input data sources and compares methods for predicting regional-scale wave power schedules over short-term planning horizons.

The paper proceeds as follows. In Section (2), the methodology for wave power data synthesis is introduced. In Section (3), the variability of the generated data is assessed. In Section (4), the operational model used to calculate the reserve impacts is introduced and applied to quantify the potential cost of wave integration. Conclusions and opportunities for future research are summarized in Section (5).

2. Wave power data synthesis

Analyzing the effects of variable resources such as wind, solar, and wave energy necessitates characterization of the variability and predictability of the energy generation. This is often a challenge as studies are required prospectively (i.e., prior to the development of the projects). This is exacerbated for resources where the technology itself has not been fully defined or developed. For this reason, modeled or observed resource time series (e.g., wave height, period, and direction) are typically input into a parameterization of the energy conversion device response.

2.1. Converter response model

While there are a number of wave energy conversion technologies available, to-date, none have emerged dominant. The various converters under development have different power ratings, and are designed to operate at different depths [21]. It is straightforward to synthesize hourly wave power data using wave measurement data and technology-specific power conversion matrices. Some matrices have been made public by the manufacturers; several other conversion matrices for converters under development have been generated from analytical models [9]. Limitations of this approach include: (1) that predictions of energy yield from wave farms can differ substantially depending on the particular converter assumed; and (2) the applicability of the conversion matrices to capture sub-hourly dynamics accurately is unclear.

Several previous studies have assumed a simplified wave-following point-absorber model [5,6,10,19]. This model assumes instantaneous power p is proportional to the available kinetic energy at time t:

$$p_t = \begin{cases} Ku_t^2 & ; Ku_t^2 \leq c \\ c & ; \text{otherwise} \end{cases} \tag{1}$$

where u is the water surface elevation velocity, K is a power proportionality constant, and c is the rated capacity of the device. The quadratic dependence on u in (1) follows from the kinetic energy available from a mass traveling at the velocity of the surface of the wave. This specification implies that power production scales linearly with the square of the water surface elevation velocity up to generator maximum power capability.

The proportionality constant represents the combined effects of wave energy converter efficiency and the size of the energy collection device (e.g., mass of a float). It is expected that real world device efficiency will vary over the range of output potential. It is also likely that the device response to high frequency components of the wave spectrum will decline as the physical size of the device increases.[1] The proportionality constant is chosen to approximate the expected average output of real world energy conversion devices. For this study the constant was chosen such that average wave project output is in the range of 30–35% of device maximum rated output (i.e., a capacity factor between 30 and 35%). A 1 MW device capacity was assumed for all study scenarios.

2.2. Array model

Measured or simulated wave data can be used to generate high-resolution surface water velocity time-series at nearby locations [6,10]. These methods characterize the wave by associating significant wave height, ocean depth, and wave period to spectral Fourier component amplitudes. This allows the development of localized wave functions from the sum of Fourier components.[2] Wave surface velocity can then be determined for any point and time around an observation site. This means that an array of point-absorber wave energy converters can be simulated near the observation site, by defining a desired array configuration and then simulating the water elevation velocity at each of the converter locations.

In this paper, we apply the methodology proposed by Brekken et al. [10] to generate the surface elevation velocity time-series at locations throughout the study region. The formulation assumes the Texel, Marsen, and Arsloe (TMA) spectrum characterizes the shape of the wave front. The TMA spectrum is an extension of the Joint North Sea Wave Program (JONSWAP) spectral shape to finite water depth [22]. The procedure proposed by Van Dongeren et al. [23] is used to translate the frequency-directional spectrum into a water surface elevation time-series. This time-series is then numerically differentiated to estimate the surface elevation velocity at times and locations in the vicinity of the observation site.

The methodology assumes ocean depth is the same throughout the array, and that individual wave converters do not affect the wave function at neighboring devices. These assumptions are not expected to cause significant error if the spacing of the devices is selected with care. Site bathymetry varies over large distances, while at distances less than 100 m, device interaction (i.e., wave attenuation) is expected to cause major impacts to energy performance [7]. We therefore chose a within-array device spacing of 100 m for the majority of the study scenarios.

The arrays considered are configured in an N_x-by-N_y gridded rectangular form, where x points towards shore, and y points along shore. The total power P produced by an array is then modeled by:

$$P_t = \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} p_{i,j,t} \tag{2}$$

where the individual converters respond according to (1). Although the frequency-directional model enables data generation on the order of seconds, the output of the converters is averaged to 1 min. This timescale is chosen because it aligns with the minimum temporal scale needed to understand large-scale operational implications of power production variability.

There are a number of limitations to the proposed simulation approach. Firstly, the arrays are of sufficient geographic scale for wave conditions to differ across each site and so the propagation

[1] Similar effects are seen in large-scale wind power generation [14].

[2] The spectral components are defined excluding relative component phase angles, which are randomly selected from a uniform distribution.