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Wave Energy Converter Arrays: Optimizing Power Production While Minimizing Environmental Effects

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Abstract

The nascent marine renewable energy (MRE) industry requires robust tools to maximize power output while evaluating the potential environmental effects of marine hydrokinetic (MHK) devices. Wave energy converter (WEC) devices in particular, are in early stages of development and may deploy a wide range of technologies to harness wave energy. The technical activities and processes used to assess WEC arrays for both power production and environmental effects requires streamlining to lower the levelized cost of wave energy projects and facilitate timely, cost-effective environmental review and compliance. A robust approach using numerical models to simulate the WEC devices and array layouts is presented that simultaneously evaluates power production and assesses environmental effects. "WEC-friendly" open-source numerical tools have been developed that are capable of assessing the environmental force on and potential changes to the environment caused by the energy extraction by WEC arrays. A case study is presented to demonstrate how the changes in WEC array configurations can be mapped and quantified using a validated model. A discussion of how changes in WEC devices and array configurations are developed to provide critical information on both engineering and environmental risk. This allows for optimization of WEC deployments to maximize power capture while minimizing environmental impacts.

Introduction

The development of offshore renewable energy projects is growing rapidly worldwide and wave energy is one of the greatest resources currently being evaluated. For example, it has been estimated that the U.S. coast’s potential contribution to total recoverable wave energy is approximately 1,200 TWh/yr (Jacobson et al., 2011). Currently, there exists a wide range of wave energy converter (WEC) technologies, broadly categorized by International Energy Agency Ocean Energy Systems to include wave active bodies (floating point absorbers), oscillating water columns, and overtopping device types (Pecher and Kofoed, 2017). Different device types and different devices within a particular device archetype can have dissimilar power production capabilities depending on, for example, project capacity (e.g., number of devices), capacity factor (e.g., capture efficiency), and availability factor (e.g., operability of a device), where the latter two factors are dependent on surface wave conditions (e.g., wave height and wave period). It has been

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shown that optimization of device type and array size and shape to wave resources is a critical component for reduction of the levelized cost of wave energy such that wave energy becomes a viable resource (Chang et al., 2018). However, an optimized WEC array (within a lease block) required to harness maximum available wave energy could number in the hundreds of individual devices per array and extend for miles along the coast. Nearshore wave propagation and circulation patterns could be potentially altered by these WEC arrays and hence, result in changes to ecosystem processes and benthic habitats of particular concern. As the industry advances from pilot- to commercial-scale projects, it is vitally important to evaluate the potential effects of WEC arrays on the natural nearshore processes that support a healthy ecosystem.

The realization of commercial-scale wave power currently relies on predictive modeling tools. These tools have been utilized to assess WEC power output and simultaneously, evaluate the likelihood of environmental impact to habitats of particular concern. At present, direct measurements of WEC power production are limited to laboratory-based or pilot-scale deployments of individual devices. Similarly, real-world quantification of the effects of different types of WEC arrays on the nearshore environment are not available. Therefore, wave and hydrodynamic model simulations provide the basis for investigations of WEC and WEC array characteristics and near- and far-field environmental effects over a range of anticipated wave conditions.

Objectives

The primary objectives of this study are to develop and evaluate tools for quantitatively assessing different wave energy conversion array design strategies and assist developers with refining site deployment plans to optimize energy capture while minimizing environmental effects.

Methodology

The present study incorporates a modified version of an industry standard wave modeling tool, SWAN (Simulating WAves Nearshore), to simulate wave propagation through deployment of hypothetical WEC arrays at a site on the Oregon coast. The modified SWAN, referred to as SNL-SWAN (Sandia National Laboratories-SWAN), includes a WEC module that modifies the native SWAN code to incorporate user-specified WEC power performance information, e.g., relative capture width (RCW) curves or device power matrices, to more accurately evaluate WEC power production and its downstream effects on wave propagation. Rather than arbitrarily choosing a transmission coefficient for native SWAN ‘obstacles’, SNL-SWAN calculates transmission coefficients for WECs (serving as SWAN obstacles) based on user-specified RCW curves or power matrices, which the industry currently uses to define WEC power production (Hagerman and Bedard, 2003). In SNL-SWAN, there are five methods, or "switches" used to calculating the transmission coefficient (Ruehl et al., 2013; 2014; Porter et al., 2014; Chang et al., 2016). The method relevant to this study is Switch 3, which employs a user-supplied WEC power matrix to estimate the transmission coefficient. This transmission coefficient is applied to each binned wave frequency based on the WEC power matrix and used to propagate incident waves past the WECs (obstacles) and estimate energy absorption. The results enable the user to accurately evaluate power production and effects on wave propagation in the lee of individual WECs and WEC arrays.

SNL-SWAN, when coupled with a hydrodynamic and sediment transport model such as Delft3D-Flow, allows for the direct investigation of WEC array effects on the physical environment (e.g. waves, currents, and the seabed). Because of the inherent coupling of all marine receptors to the physical environment, a quantitative evaluation of its stressors provides the basis for any environmental assessment using, for example, the Spatial Environmental Assessment Tool (SEAT; Jones et al., 2018). The SEAT provides a tool for qualitatively and quantitatively evaluating environmental stressors and receptors in regions affected by the WEC array deployment. SEAT results are spatial maps that quantify potential changes to the hydrodynamic environment and sediment dynamics that may affect water quality and seabed characteristics, which may alter benthic habitats of particular concern and ecological functions. The SEAT’s intention is to an efficiently link scientific knowledge and the regulatory process while simultaneously identifying optimal WEC deployment strategies that minimize environmental impacts while maximizing power production.

Case Study

The selected case study modeling site was the Oregon coast, offshore of Newport, OR, at a designated WEC test site – the Pacific Marine Energy Center (PMEC) North Energy Test Site (NETS; now known as PacWave-North, or PWN) (Figure 1). Waves, circulation, and sediment transport were modeled using the SNL-SWAN module and incorporated into the open source Delft3D framework (Gerritsen et al., 2008, Ruehl, et al., 2015). The coupled Delft3D-SNL-SWAN model results were used to calculate probability-based risk metrics for sediment mobility. Model simulated WECs were treated as obstacles that induce shadowing effects and allow some wave energy to be propagated, with the balance absorbed by the WECs. The case study utilized SNL-SWAN Switch 3 (WEC power matrix used to compute the transmission coefficient, which is applied to each binned wave frequency).

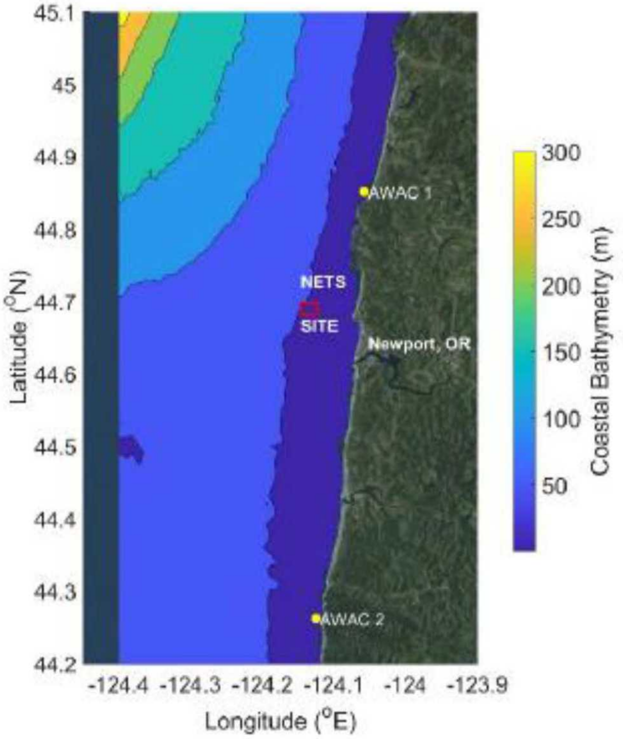

Figure 1—Numerical model domain showing coastal bathymetry and the location of the North Energy Test Site (NETS, now known as PacWave-North; red box) where wave energy converter deployments were simulated. (AWAC 1 and AWAC 2 are the deployment locations of acoustic wave and current meters that were used for model validation.)

The WEC device considered for this case study was the floating oscillating water column (F-OWC), inspired by the OE Buoy (Ocean Energy Ltd.; Babarit et al., 2012). The device has a maximum horizontal dimension of 50 m and maximum power output of 3,310 kW. Its power matrix represents power absorption by the WEC as a function of sea state as described by wave heights and periods (Figure 2). Details regarding model set-up (computational grid spacing, boundary conditions, time steps, initial conditions and probability of occurrence of initial wave conditions/events, etc.), model validation, and calculation of risk metrics for the Newport, OR case study can be found in Jones et al. (2018).

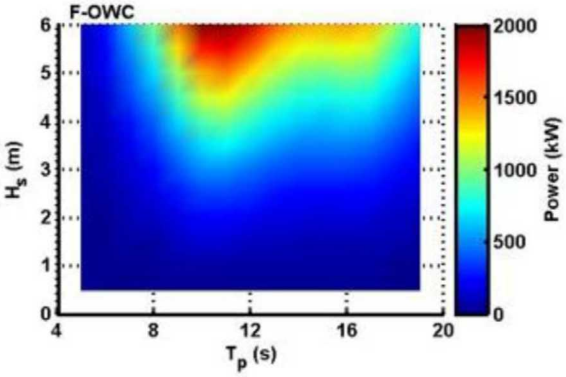

Figure 2—Power matrix for the F-OWC WEC device (Babarit et al., 2012).

SEAT modeling and assessment steps (Figure 3) were undertaken with the goal of informing developers, regulators, and stakeholders on the effects of array shape on potential sediment mobility. Eight types of WEC array configurations were examined. The number of WECs in each array configuration was held constant at 28 devices, with four simulated WECs in the east-west direction, and seven WECs in the north-south orientation. Inter-device spacings were varied while ensuring that the WEC array remained within the confines of the permitted NETS (or PWN) site (Figure 4). The cases were named to reflect the inter-device spacing as the number of model grid cells in longitude and latitude respectively (e.g., 4x4, 12x6, etc.). It is worth noting that the east-west and north-south grid resolutions differ; therefore a spacing of, e.g., ‘4’ in longitude is smaller than a spacing of ‘4’ in latitude.

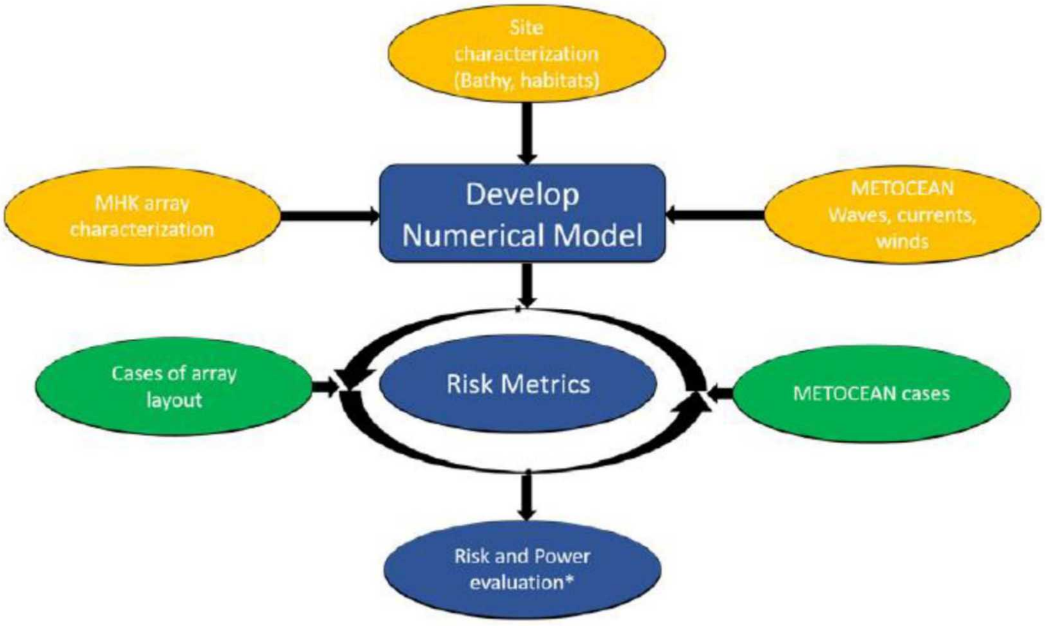

Figure 3—SEAT modeling and assessment steps.

An annual climatological set of wave events and their associated probabilities (not accounting for extreme events; see Jones et al., 2018) were applied to each of the WEC array layouts to examine changes in sediment mobility associated with each array configuration. Probabilistic risk metrics associated with sediment mobility were computed using the probability of occurence of each wave event, taking into account wave power absorption by each WEC array layout and its effect on the wave field and circulation patterns. Total risk of sediment mobility was then compared to total power absorption by the WEC array to help determine optimal array configurations that maximize power absorption while minimizing risk.

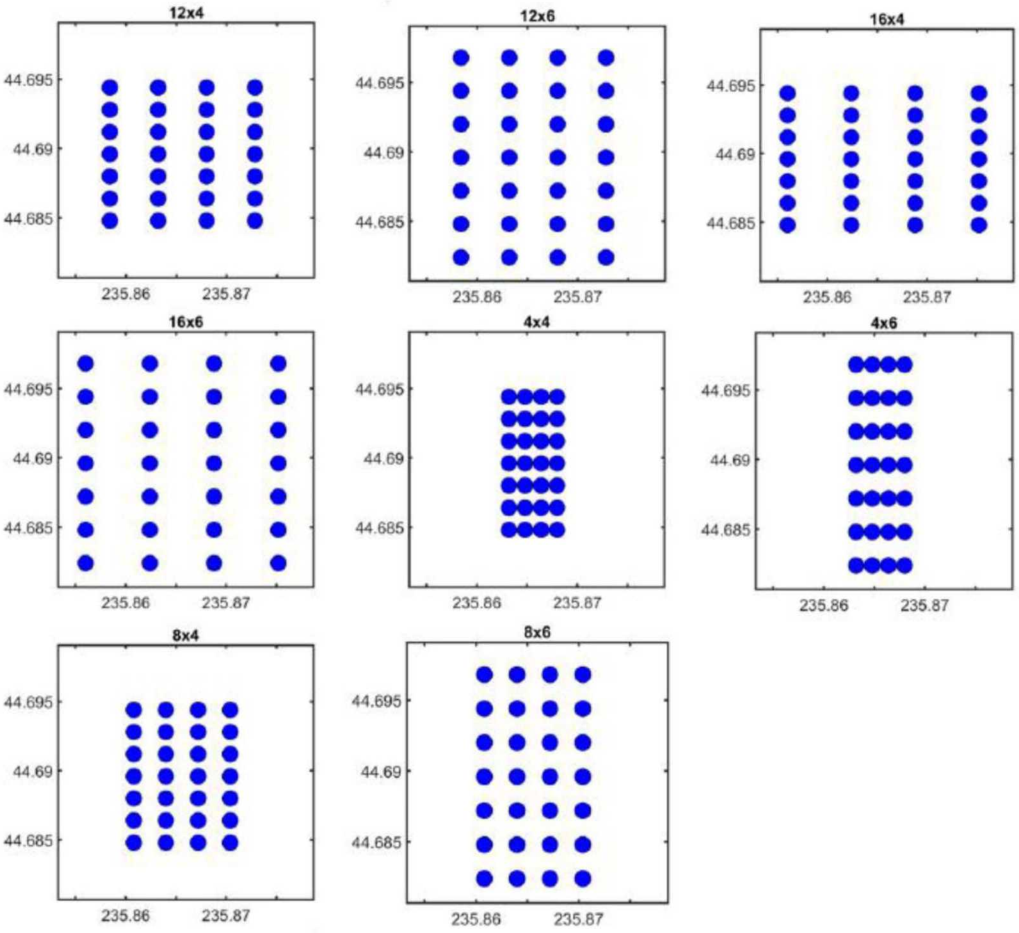

Figure 4—Eight WEC array layouts evaluated for total power absorption and risk to sediment mobility. Each layout is titled according to its inter-device spacing where, e.g., 12x4 represents 12 grid cell spacing in the east-west (longitudinal) direction and 4 model grid cell spacing in the north-south (latitudinal) direction.

Results and Discussion

The Delft3D-SNL-SWAN model computes power absorption by each simulated WEC (obstacle), thereby enabling evaluation of total power absorbed by WEC arrays of varying configurations. Expectedly, model results indicate that the lowest amount of power is absorbed by the ‘4x4’ array (Figure 5). This tightly clustered array results in increased wave shadowing from neighboring WECs, resulting in the observed lower power absorption. Conversely, the array layout with the largest inter-device spacing, the ‘16x6’ array, has the largest power absorption (Figure 5).

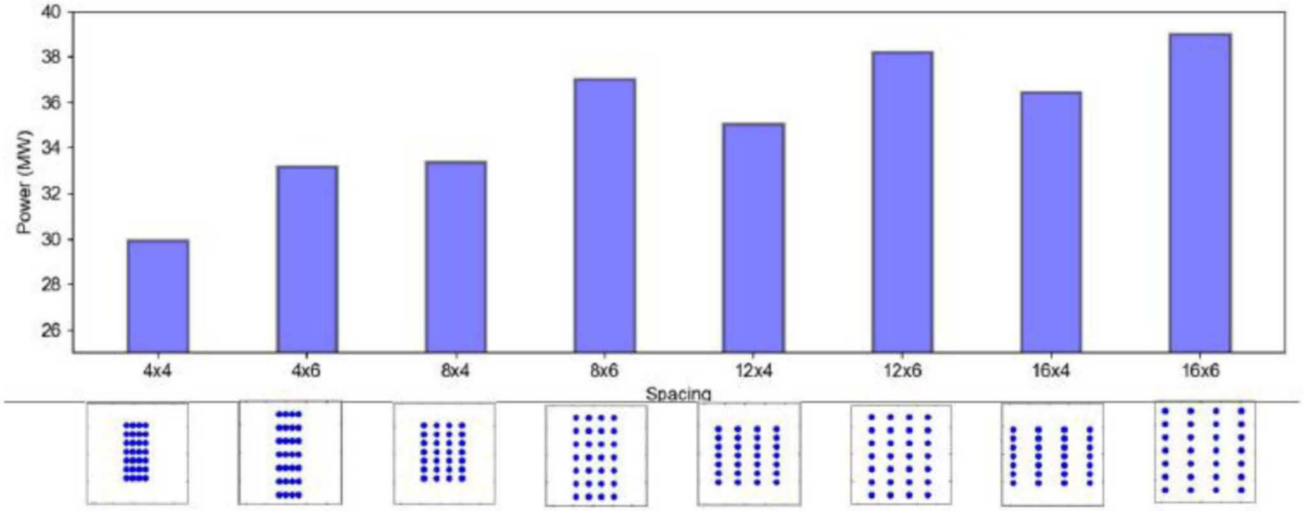

Figure 5—Total power absorbed by the simulated WEC array as a function of array configuration.

These results, used in the SEAT probabilistic risk evaluation framework (Figure 3), can also provide information regarding array configurations that would likely result in changes to, e.g., sediment mobility and seabed elevation (i.e. alteration of benthic habitats of particular concern), larval motility, or other physical or ecological risk metrics. Case study results show that the lowest power absorption by the 4x4 array results in the lowest risk of sediment mobility (Figure 6). Similarly, there are increases in the risk of sediment mobility as the power absorption increases, such as for the 8x6, 12x6 and 16x6 arrays (Figure 6). Interestingly, the 16x4 array shows power absorption on the higher end of those modeled by the various cases (greater than 36 MW; Figure 5), but exhibits relatively low risk in terms of sediment mobility, particularly in comparison to the 8x6, 12x4, 12x6, and 16x6 array configurations (Figure 6). This is likely a consequence of the smaller array spacing resulting in greater velocity reductions in the lee of the array.

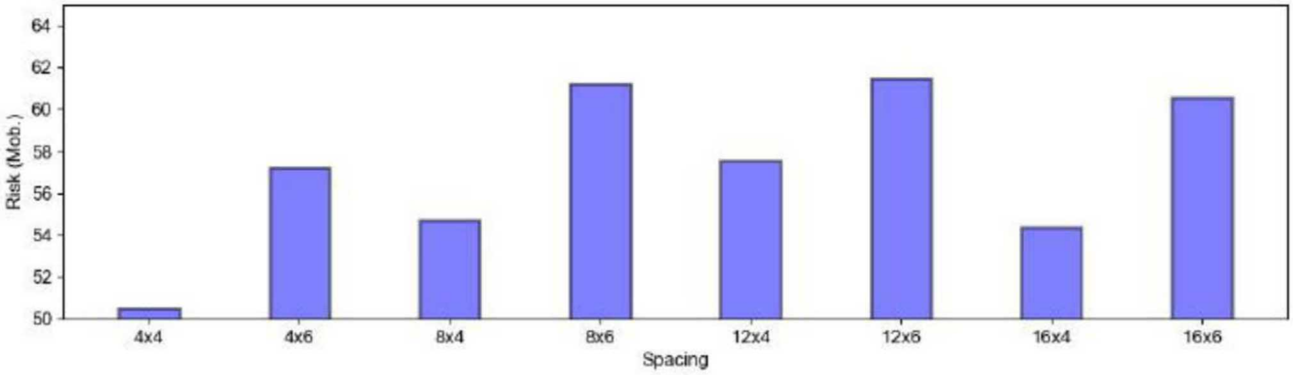

Figure 6—Risk of sediment mobility (benthic habitats of particular conern) as a function of array configuration.

Modest changes in the risk of sediment mobility were seen as a consequence of varying inter-device spacing. These changes are mainly located in the direct vicinity of the WEC array, no matter its overall size, where small changes in sediment deposition can be expected. The resulting risk metrics did not indicate an overall change in erosion versus deposition over the model domain.

The approach presented here enables optimization of WEC array layout in terms of maximizing power absorption while minimizing environmental risk. For the purpose of this case study, while lower power absorption generally reflects lower risk, specifics of the array configuration and wave conditions reveal that particular cases such as the 16x4 array are optimal (Figure 7). This analysis reveals the utility of SEAT in informing stakeholders, regulators and developers about the benefits of an informed analysis that takes into account array layouts, site specific modeling and knowledge of wave dynamics to yield array shapes and layouts that satisfy multiple, often competing requirements.

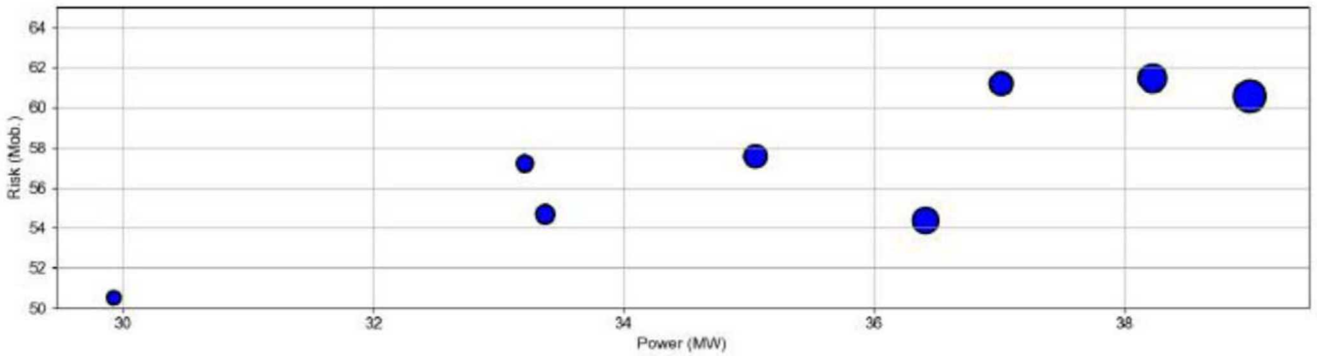

Figure 7—Risk of sediment mobility as a function of total power absorbed by a WEC array. The sizes of the blue dots are scaled to the size of the simulated WEC array (e.g. the smallest dot is the 4x4 array and the largest dot is the 16x6 array).

The NETS/PWN site on the Oregon coast provides an excellent test bed for developing and demonstrating the effectiveness of coupled Delft3D-SNL-SWAN model and the SEAT framework. Further work will be done to refine the technique by applying Delft3D-SNL-SWAN and ultimately the SEAT to a new reference site. Reference sites being considered include PacWave-South (PWS; formerly known as the PMEC South Energy Test Site (SETS)) and Yakutat, Alaska. PacWave is a full-scale wave energy converter testing facility funded by the U.S. Department of Energy that is currently under development. It allows for a comparison to NETS/PWN, which is very similar to PWS, but will be an operational grid-connected WEC testing site that can provide essential model validation information. The Yakutat, Alaska site is being considered for a wave energy installation to power remote coastlines. This work will include the latest improvements to power-performance integrated into Delft3D-SNL-SWAN to ensure the most accurate representation of each device and the array as a whole. The SEAT was not developed with solely WEC devices or arrays in mind. The goal wass to have a device agnostic set of steps that any developer of ocean energy devices, including offshore wind, could follow to support the design and risk mitigation process. To this end, the SEAT will be applied to a tidal energy site to ensure the guidance is effective in addressing the needs of current energy converters.

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