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NORTHWEST NATIONAL MARINE RENEWABLE ENERGY CENTER
FINAL SCIENTIFIC/TECHNICAL REPORT

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EXECUTIVE SUMMARY

In 2008, the US Department of Energy's (DOE) Wind and Water Power Program issued a funding opportunity announcement to establish university-led National Marine Renewable Energy Centers. Oregon State University and the University of Washington combined their capabilities in wave and tidal energy to establish the Northwest National Marine Renewable Energy Center, or NNMREC. NNMREC's scope included research and testing in the following topic areas:

- Advanced Wave Forecasting Technologies;
- Device and Array Optimization;
- Integrated and Standardized Test Facility Development;
- Investigate the Compatibility of Marine Energy Technologies with Environment, Fisheries and other Marine Resources;
- Increased Reliability and Survivability of Marine Energy Systems;
- Collaboration/Optimization with Marine Renewable and Other Renewable Energy Resources.

To support the last topic, the National Renewable Energy Laboratory (NREL) was brought onto the team, particularly to assist with testing protocols, grid integration, and testing instrumentation.

NNMREC's mission is to facilitate the development of marine energy technology, to inform regulatory and policy decisions, and to close key gaps in scientific understanding with a focus on workforce development. In this, NNMREC achieves DOE's goals and objectives and remains aligned with the research and educational mission of universities.

In 2012, DOE provided NNMREC an opportunity to propose an additional effort to begin work on a utility scale, grid connected wave energy test facility. That project, initially referred to as the Pacific Marine Energy Center, is now referred to as the Pacific Marine Energy Center South Energy Test Site (PMEC-SETS) and involves work directly toward establishing the facility, which will be in Newport Oregon, as well as supporting instrumentation for wave energy converter testing.

This report contains a breakdown per subtask of the funded project. Under each subtask, the following are presented and discussed where appropriate: the initial objective or hypothesis; an overview of accomplishments and approaches used; any problems encountered or departures from planned methodology over the life of the project; impacts of the problems or rescoping of the project; how accomplishments compared with original project goals; and deliverables under the subtasks. Products and models developed under the award are also included.

GOALS AND OBJECTIVES OF THIS RESEARCH

ADVANCED WAVE FORECASTING TECHNOLOGIES (TASKS 1, 7, 13)

ORIGINAL HYPOTHESES OR SCOPE

The original scope for these tasks was to provide the capability of integrating wave energy into the electrical grid with proper forecasting protocols. Wave forecasting technologies can enhance the integration of Wave Energy Converters (WECs) into the electrical grid by providing predictions of the expected wave power at the site of a WEC array. Wave/structure and electromechanical modeling of the WEC can then produce predictions of the expected power output from an array.

A major roadblock in the integration of power from WECs into the electrical grid is the temporally variable nature of the extracted power, requiring other forms of (potentially expensive) power to balance the load. At the same time, the predictability of the wave resource is a major advantage over other renewable energy resources such as terrestrial wind. Wave forecasting technologies can therefore facilitate the integration of WEC into the electrical grid by providing predictions of the expected wave characteristics at the site of a WEC array. Wave/structure and electromechanical modeling of the WEC can then produce predictions of the expected power output from an array. Wave forecasting results can also lead to long-term reference data sets that can be used for regional or site-specific resource characterization studies. Before NNMREC, accurate wave forecasts along the Oregon coast were not available for the water depths that were being considered by WEC developers and validation of prediction models during a variety of conditions had not been carried out.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

NNMREC's approach to these tasks involved the use of the numerical wave modeling code WAVEWATCH III developed by the National Center for Environmental Predictions (NCEP) associated with the National Oceanographic and Atmospheric Association (NOAA). The code had recently been updated to include physics packages that made its applicability to nearshore environments possible. NNMREC opted to execute in house daily model runs associated with the global and Eastern North Pacific domains and use these results to make forecasts over a local grid that covered the Oregon Continental Shelf at high resolution (see Garcia-Medina et al., 2013).

The research conducted by Ozkan-Haller's team has provided 84-hour high-quality and validated forecasts (see Figure 1). The extensive data case with the forecasts is helpful for further localized resource characterization for developers who are looking at specific locations as potential deployment sites.

The forecasting model is run once a day at 1200 UTC producing 84 hour forecasts. The series of nested grids with increasing resolution shoreward achieve a 30 arc-second resolution at the shelf level. Normalized root-mean-squared-errors in significant wave height and mean wave period range from 0.13 to 0.24 and 0.13 to 0.26, respectively. Visualization of the forecasts is made available online through the Northwest Association of Networked Ocean Observing Systems (NANOOS) Visualization System (www.nanoos.org).

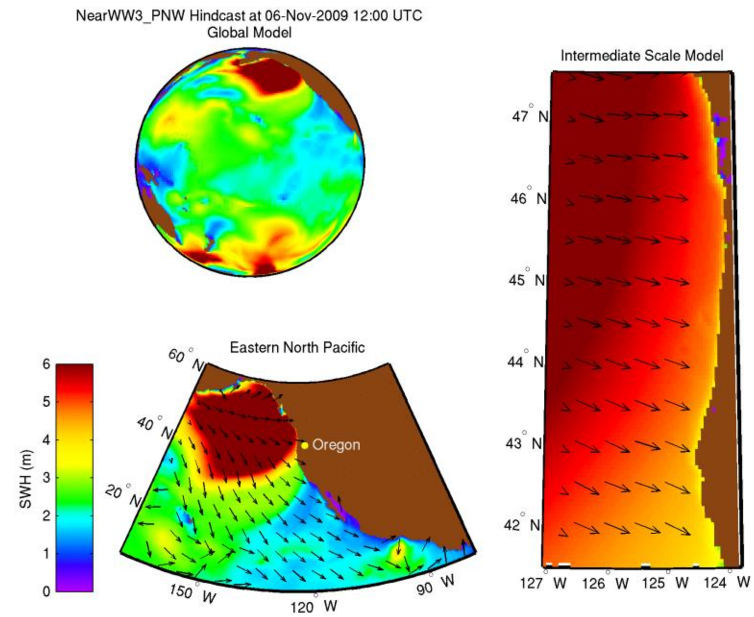

Figure 1: The global (top left), Eastern North Pacific (bottom left) domains that are identical to those used by the National Center for Environmental Prediction, and the local Oregon domain (right panel). The grids covering the domains have increasing resolution, resulting in predictions over 600 – 900m.

A series of simulations taking advantage of a validated shelf scale numerical wave model suggest that neither dissipation due to bottom friction nor wind generation are important in the region at this scale for wave forecasting and hindcasting when considering bulk parameters, as opposed to the processes of refraction and shoaling. The Astoria and McArthur Canyons; the Stonewall, Perpetua, and Heceta Banks; and Cape Blanco are significant bathymetric features that are shown to be capable of producing alongshore variability of wave heights on the shelf (see Figure 2).

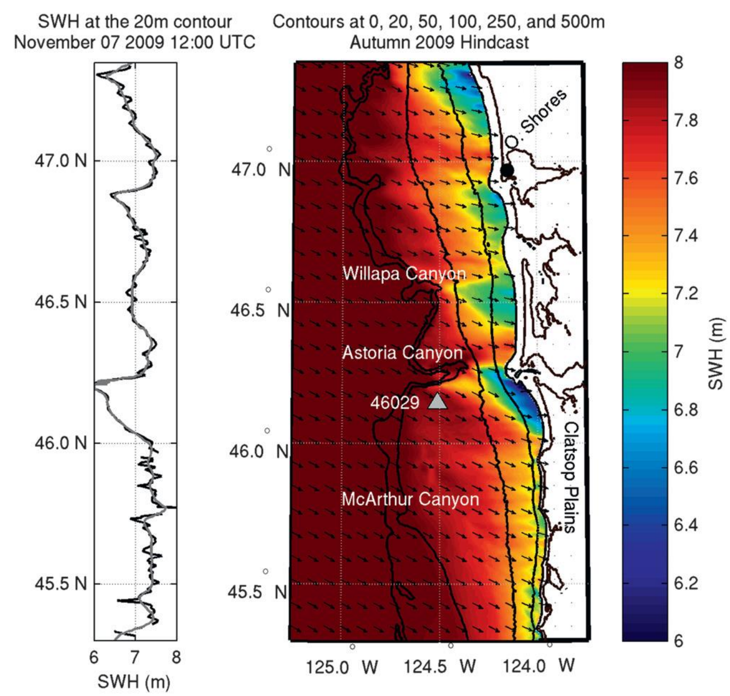

Figure 2: Significant wave height (SWH) along Oregon coast at 20 m contour, 11/7/09 (left); SWH along Oregon coast at 0, 20, 50, 100, 250,500 m contours, 8/09 hindcast (right).

The presence of a forecasting model for the Oregon Coast also provides the ability to carry out an assessment of the wave resource in Oregon at locations where direct observations are not available. For this purpose, the results of a 7 year hindcast were generated at a 30 arc-second resolution using the numerical models WAVEWATCH III and SWAN

(Simulating WAves Nearshore, available on Sourceforge). The hindcast accuracy was quantified by comparing model output to measured buoy data yielding linear correlation coefficients of around 0.90 for the significant wave height. The resulting study described the alongshore variability of the resource over the continental shelf. The general decline of the wave power with depth is explained by considerations of wave refraction and shoaling. Further, due to wave refraction, areas off the central and southwest Oregon coast are identified that show increased wave power at 50m of water in comparison with the 250m value. These areas also show increased temporal variability. In addition, areas with preferentially narrower wave spectra in both frequency and direction are identified off southwest Oregon. General trends in the directionality of the resource indicate a systematic switch in the wave direction with latitude. The seasonality of the resource is also assessed in terms of variability and trends relevant to the planning and deployment of wave energy converters. The continental shelf is mapped in terms of the coefficient of variability, which is greater (smaller) than unity during the summer (winter) and regardless of the season is smaller in southwest Oregon (see Figure 3).

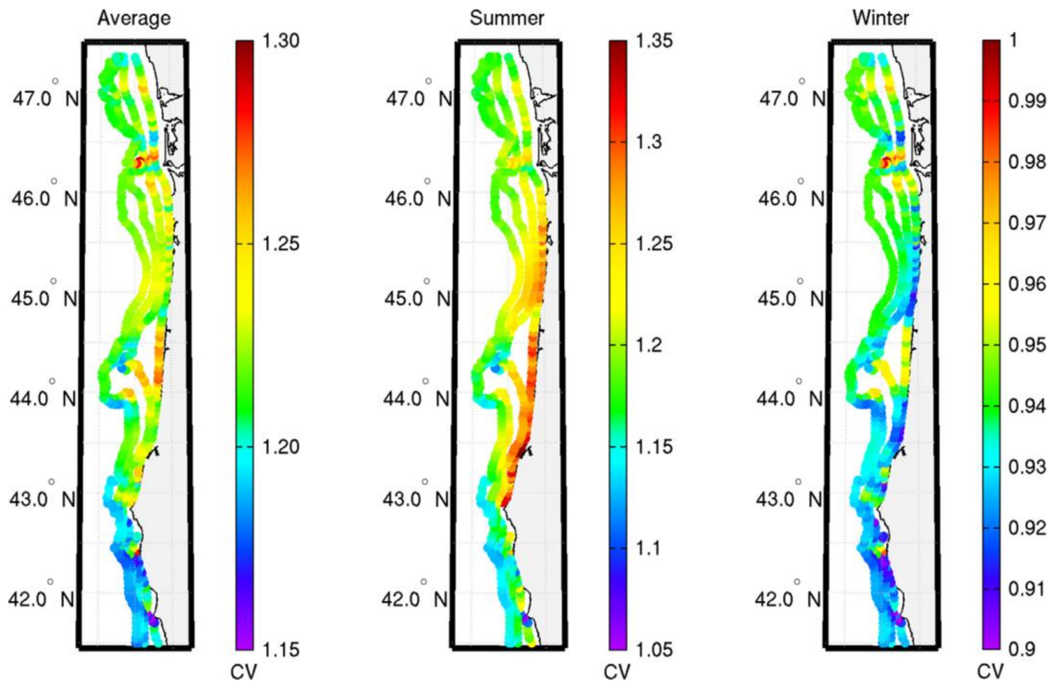

Figure 3: Normalized variability of wave power along Oregon coast; red indicates high variability.

In the proposal for this task, it was assumed that high accuracy forecasts may not be possible on the continental shelf with physics-based models alone and it was argued that advanced neural network (ANN) methods would have to be employed. However, the accuracies in predicting wave-related quantities with the physics-based models turned out to be very high at the longer time scales of hours and longer. That said, ANN methods proved useful in the prediction of shorter term variability (see Parkinson et al., 2015; Gillespie, 2015).

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

There were no significant barriers to this task and as noted above, the physics based wave model was sufficient to satisfy the goals of this study. The incorporation of ANN methods turned out to be less significant than the team had initially expected.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The visualization of forecasts developed under this line of inquiry available on the NANOOS website fulfills the deliverables and research outcomes specified under this project objective. In support of this physical deliverable are publications listed at the end of this section. This work meets the original goal of a near shore wave model incorporating a simplified representation of WECs, with testing as wave observations come online.

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DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix A.

DEVICE AND ARRAY OPTIMIZATION – WAVE ENERGY (TASKS 2.1, 8.1, 14.1)

ORIGINAL HYPOTHESES OR SCOPE

Given estimates of the available wave power to a WEC, prediction of the power output from the device requires an understanding of how the WEC will move in the ocean, how the WEC will affect the ocean wave field, and the forces acting on the WEC as well as the power capture, variability and efficiency of the WEC. In addition, feedback mechanisms exist between these components; hence, an integrative modeling approach is required.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

Work related to device and array optimization has been a major focus area for NNMREC with many contributing PIs. In particular, the areas of effort have included: 1) design, manufacture, and testing of prototype WECs; 2) frequency-domain modeling as well as nonlinear time-domain modeling of WECs and arrays (including a formal guide for developers on these issues); and 3) parameterizations of WEC and array dynamics for regional-scale wave models. Accomplishments in these areas are discussed further below.

A key component in bringing ocean WECs from concept to commercialization is to design, build, and test scaled prototypes to provide model validation for WEC and array optimization models. Two efforts have been undertaken along these lines at Oregon State University (OSU) under this award.

In the first project, two PhD students, Lewis and Bosma, worked with their faculty advisors, von Jouanne and Brekken, on the development of an Autonomous Wave Energy Converter (AWEC), for low power autonomous and remote applications (200 W continuous). A one-quarter scale prototype of an autonomous two-body heaving point absorber was designed, built and tested; the design is shown in Figure 4. Specifically, they tested the AWEC on the wave energy linear test bed in the Wallace Energy Systems and Renewables Facility (WESRF) (see Figure 5), and in OSU swimming pools. These pool tests were to optimize the buoyancy in preparation for wave tank testing in the O. H. Hinsdale Wave Research Lab's Large Wave Flume (see Figure 6).

Power produced during wave tank testing is shown in Figure 7. This work will serve as a guide for future developers of WECs, providing insight to the process involved in taking their concept to prototype stage.

At a more "general" level, Brekken and Bosma focused on creating a testing guide for developers (see Bosma (2012), Bosma (2013)). This guide is meant to provide basic instruction and examples in WEC modeling and performance

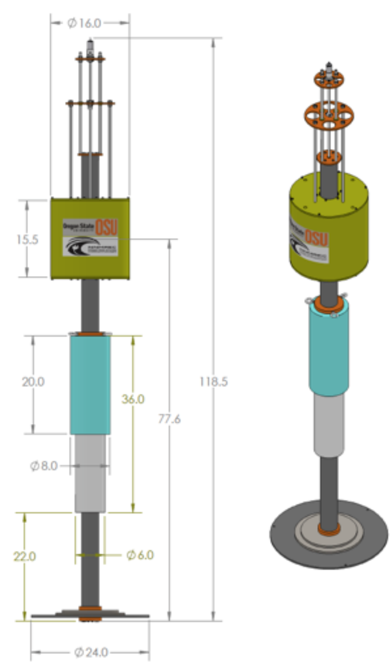

Figure 4: AWEC design concept.

Figure 5: AWEC Testing on the wave energy Linear Test Bed in WESRF.

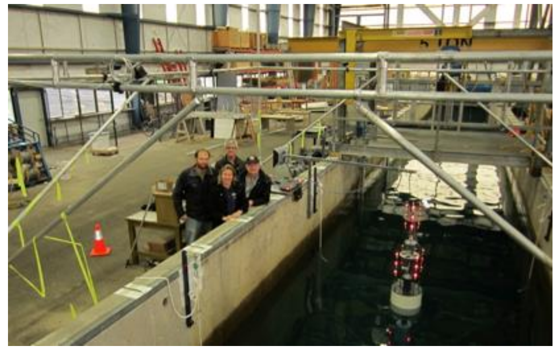

Figure 6: AWEC testing O.H Hinsdale facility Large Wave Flume.

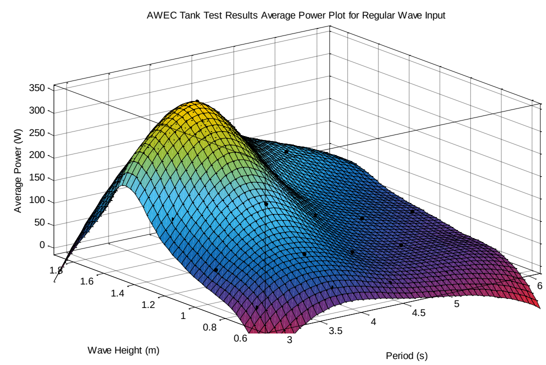

Figure 7: Power produced by AWEC in tank testing.

estimation in four main areas: frequency domain analysis; time-domain and frequency-domain hybrid analysis; fully non-linear time-domain analysis; and hardware tank testing.

The guide outlines the design methodology necessary to perform frequency domain analysis on a generic WEC. A two-body point absorber representing a generic popular design was chosen and a general procedure is presented showing the process to obtain first pass preliminary performance results. New developers can adapt the procedure to their particular WEC design and wave conditions, which will provide the first steps toward a cost of energy estimate. This framework will serve the industry by providing a sound methodology to accelerate the new development of WECs.

Frequency domain analysis serves as the first step in the design process. Goals of frequency domain modeling include defining the WEC parameters, defining a mooring configuration and power take off system, and getting a first impression of how the WEC will perform. Because frequency domain analysis is intrinsically linear, many real nonlinear effects that become prominent under high and extreme sea conditions are not taken into account and results should be viewed with this in mind. As such, the frequency domain analysis provides an insightful look at a preliminary design and WEC performance for normal energy conversion operation. Basic shape optimization, identification of resonant frequencies of the WEC, structure loading due to wave pressures, general frequency response characteristics, and power output characteristics are to be gained by this analysis.

In the area of WEC-array studies, Haller's group has developed a WEC-array parameterization that can be implemented in spectral wave models at field scales. Specifically, they developed a parameterization based on the WEC-array experimental dataset that was conducted under other DOE funding and performed at the Hinsdale Wave Lab in collaboration with Columbia Power Technologies. This parameterization is appropriate for field-scale modeling efforts and provides a tool for assessing how WEC arrays affect the wave climate in the far-field (i.e. nearshore). In this methodology, arrays are represented in SWAN through the external modification of the wave spectra at the WEC locations, based on the experimentally determined Power Transfer Function. Changes in nearshore forcing conditions for each array size and configuration were compared in order to determine the scale of the far-field effects of WEC arrays and which array sizes and configurations could have the most significant impacts on coastal processes (see Figure 8).

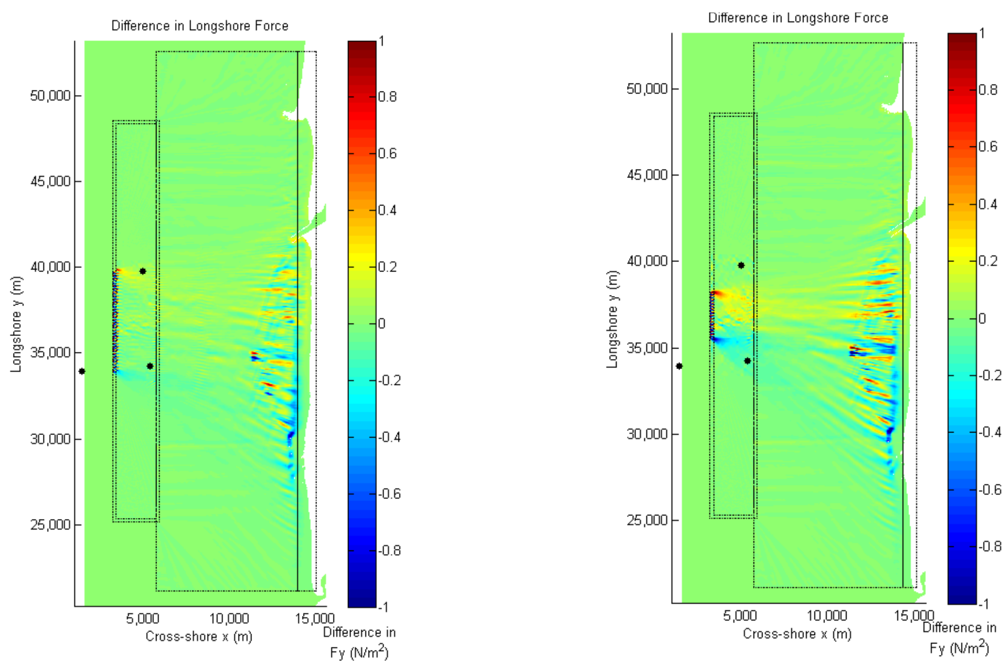

Figure 8: Difference in longshore force of WEC arrays modeled at PMEC-SETS, NNMREC's planned deep water grid connected test facility at Newport, OR. Comparison of 10x (left) and 4x (right) spacing of WECs Significant wave height approximately 5.45 meters, mean direction approximately -27 d, wave period approximately 12.6 seconds.

Oskamp and Ozkan-Haller (2012) implemented a wave-structure interaction model, and estimated power output for a simplified wave energy converter operating in measured spectral wave conditions. In order to estimate power output from a wave energy converter, WEC response to hydrodynamic forces was computed using a boundary element method potential flow model. A method was outlined for using the hydrodynamic response to estimate power output. This method was demonstrated by considering an idealized nonresonating WEC with one year of measured spectral wave conditions from the Oregon coast. The power calculation was performed in the frequency domain assuming a passive tuning system which was tuned at time scales ranging from hourly to annually. It was found that there was only a 3% gain in productivity by tuning hourly over tuning annually, suggesting that for a non-resonating wave energy converter, power output is not very sensitive to the value of the power take off damping. Interaction between wave energy converters in arrays was also considered, and results for an array of idealized point absorbers suggest that interactions are minimal when WECs are placed 10 diameters apart from each other.

McNatt (2012) investigated the behavior of an array of multiple WECs using a wave/structure interaction model similar to Oskamp and Ozkan-Haller (2012) and examined the modification to the wave field due to the presence of the WECs. One important finding of this work has been related to two different kinds of WECs. When comparing near-resonant WECs and wave-following WECs that extract the same amount of energy, this work showed that the near-resonant WECs scatter more wave energy compared to the wave-following WECs and, therefore, induce a much larger far-field effect in the lee of the WECs. Note that the compared WECs extracted identical amounts of energy from the wave field.

One of the efforts focused on modeling arrays showed power variability of a wave power park (i.e., array) (Brekken et al. (2012)). The array was made up of 400 WECs, each 250 kW, for a total park rated power of 100 MW. The results showed that the 0.5 second standard deviation of a 100 MW wave park was around several MW, which was only a few percent of the average park power output. Thus the short term variability of a large array was quite small. The long term variability was larger, where the 10 minute variability can change by up to 50% of the mean output.

In another effort, a comprehensive approach to analytical and numerical wave models on coupled fluid-structure interaction for WEC was developed and field tests were conducted in this project. To fully understand the physics of wave loads on WECs especially due to impact, physical model tests in the large-scale wave-basin environment was also a major focus (see Figure 9). The numerical models employed in-house software including a potential-flow code to model the far field and another based on viscous-flow code to model the near field around the WEC. Two commercial software packages, AQWA and LS-DYNA, were also employed. Fundamental development on the potential theory was performed (see Nimmala et al. (2012, 2013)), and viscous flow and coupling between potential and viscous flow was investigated (see Zhang, Peszynska and Yim (2013); Zhang, Del Pin and Yim (2014); Zhang, Yim and Del Pin (2015)). Application of the theory and numerical models to wave-basin physical modeling and testing was described in Zhang and Yim (2015a) with data analysis in Zhang and Yim (2015b, 2015c). Because there are no available measurements of wave impact on WECs, the fluid-structure impact interaction effects were studied from a fundamental setting of wedge entry (which data are available in-house). The numerical models developed in the project were found to be able to predict the peak pressure well as shown in Figure 10 (see Challa et al. 2010a & b, and 2014a & b, Zhang et al. 2015).

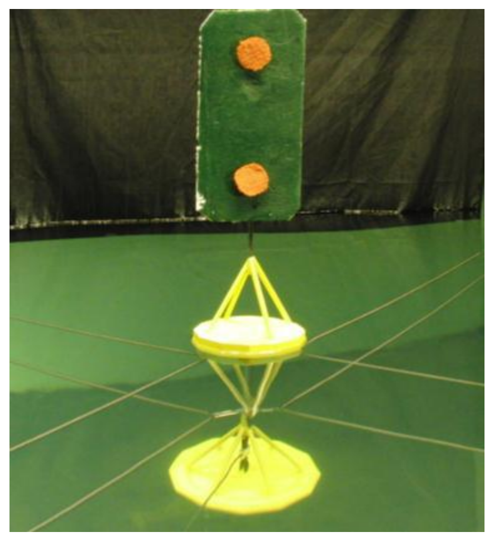

Figure 9: Wave tank test of a locked-body floating point absorber system.

In the latter part of the project, a large amount of effort has shifted to WEC-Sim. A study validating the performance of WEC-Sim for a complex multi-body WEC was just completed and a journal paper on the topic is currently under review. This has significance for array modeling as multibody WECs are a form of closely coupled array. The results in Figure 11 are from the WEC-Sim study and demonstrate the agreement from WEC-Sim in predicting the range of motion for a Columbia Power field deployed WEC in the form of Cumulative Distribution Functions.

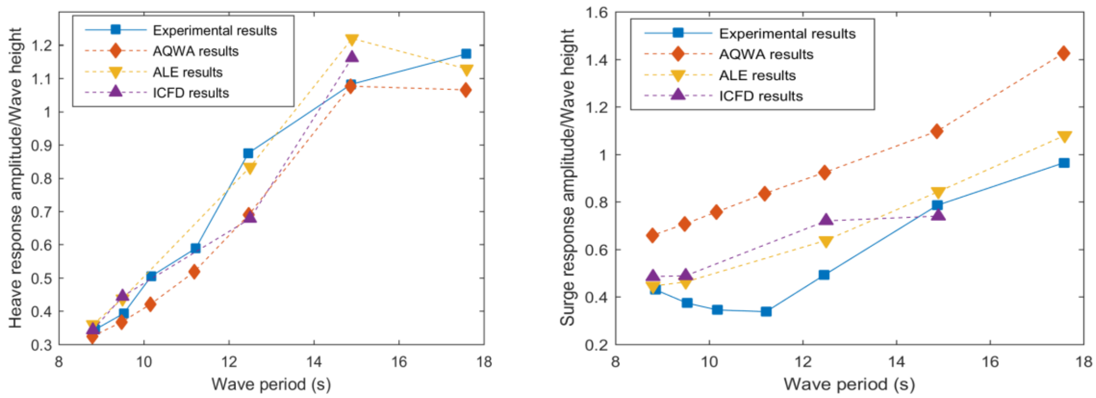

Figure 10: Comparison of response amplitudes between numerical results and experimental data; in-house code labeled as ICFD results.

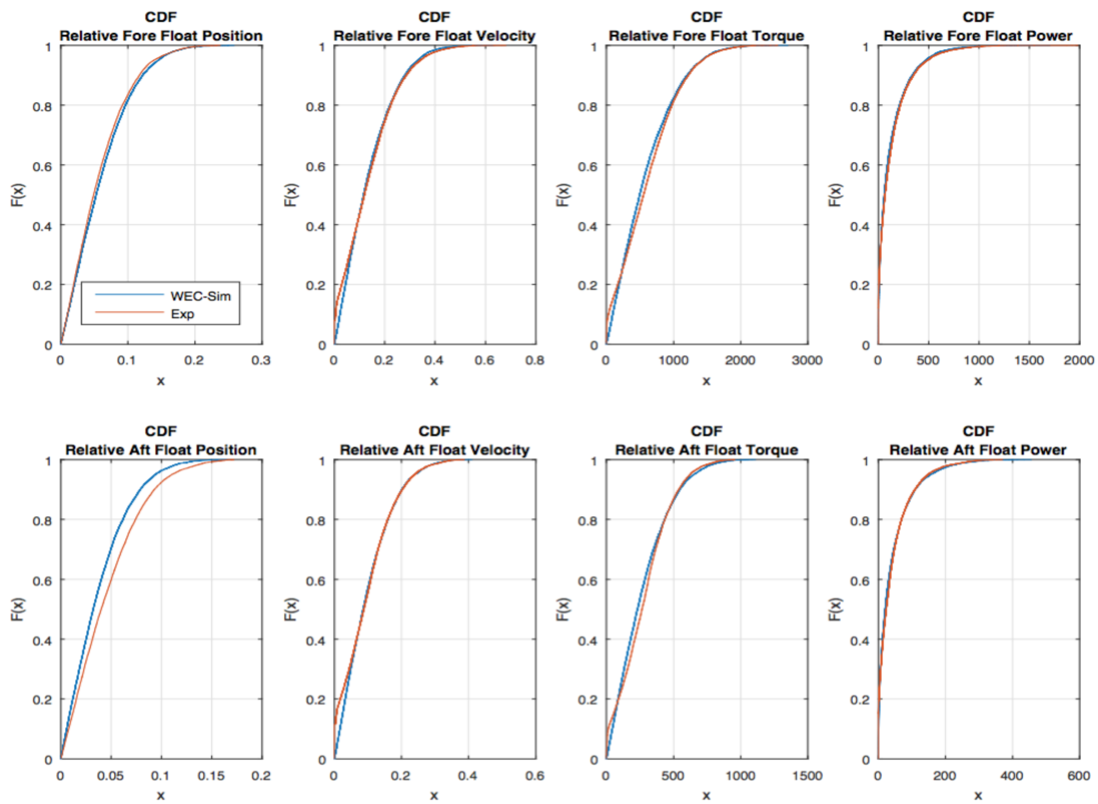

Figure 11: Experimental data vs. WEC-Sim predictions for Columba Power WEC.

To provide data to assess the accuracy of the in-house numerical models developed and the commercial codes used, a series of large-scale laboratory experiment and field tests were conducted. The laboratory experiments focused on providing high-resolution data of the dynamic motions of a novel wave energy converter (see Rhinefrank et al. (2010a), (2010b), and (2013)). Scaled models were also deployed in the ocean for field trials and data collection. The first set of sea trail tests using a 1/33-scale model was conducted by the OSU WEC group as document in Elwood et al. (2010a), (2010b), and (2011). A larger, 1/7-scale model was conducted in Puget Sound, Washington (see Rhinefrank et al. (2011)). Evaluations of accuracy of numerical simulations are near completion and will be documented in a PhD thesis in 2016.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

The efforts within this project objective experienced no major difficulties but became more highly focused around numerical modeling of WEC behavior and optimization than had initially been anticipated. At the time of proposal submission, the team anticipated that there would be significant numbers of WECs tested with the Ocean Sentinel at the NETS site, and that did not happen due to lack of funding for such activities. Because no "representative" full-scales WECs were available to be modeled during the course of the project, yet test data was available from large-scale wave basin tests of simpler but similar WECs, numerical simulations were modified to model available wave basin tests.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The original scope of work focused on the development of an integrated modeling tool. As efforts were made in this direction it was identified that a greater impact could be made by coupling efforts with the ongoing WEC-Sim project, as that achieved many of the same goals. Thus much of the effort of Brekken's team focused on WEC and array models that are important for controls implementation and time-domain modeling. Much of this work has been integrated into WEC-Sim and efforts are ongoing with the continued development of the WEC-Sim modules, PTO-Sim, and Control-Sim.

The work on a near shore wave model for the test berth site aligned the original goal, incorporating a simplified representation of WECs, with testing as wave observations come online.

The original objectives of developing accurate multiscale numerical models and validation with experimental data were achieved. Modeling of complex WECs can be accomplished using the same tools developed under this award. Field configurations and measured data were not available for model development and analysis until recently. Since then, efforts shifted to analysis of the field data and validation of numerical models using the field data.

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DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix B.

DEVICE AND ARRAY OPTIMIZATION – TIDAL ENERGY (TASKS 2.2, 8.2, 14.2)

ORIGINAL HYPOTHESES OR SCOPE

Due to the highly localized nature of the in-stream resource, the space available for array development is limited. Therefore, it will be important to optimize array deployment within tidal channels. This will require an understanding of the potential for arrays to substantially divert high velocity flows and an understanding of the maximum packing density for individual devices. Additionally, the tolerance of MHK turbines to fluctuations in the incoming velocity, due to turbulence or wake of upstream turbines will play an essential role in their efficiency and therefore their ability to convert energy into electricity in an economic manner. The highly confined nature of the tidal channels where the velocity is high enough to promote MHK energy conversion, by its very nature, will significantly influence how wakes evolve (away from the canonical free momentum conserving turbulent wake) and impact other turbines in the array.

Similarly, low-cost approaches are required to allow individual devices and arrays to resist loads induced by currents. While most designs to date have relied on pile or gravity foundations, compliant moorings may allow for lower costs, provided that the increase in dynamic complexity can be accounted for.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

Aliseda and his team have developed a hierarchy of existing numerical models with applications to MHK hydrodynamic modeling. Simulation efforts started with a simple actuator disk model, extending into the blade model and going into the blade-resolved rotating reference frame model. The accuracy of the rotating frame model to simulate the pressure coefficient on specific blade sections, as measured in wind tunnel experiments on the NREL Phase VI wind turbine was analyzed. Based on the results observed from the three dimensional velocity and pressure fields from the rotating reference frame simulations and published experiments, and the comparison with results obtained from 2D lift and drag coefficients for the blade elements, a method was developed to use the results from blade-resolving rotating reference frame simulations to inform the Blade Element Model simulations improving their accuracy. This methodology development was based on the NREL Phase VI wind turbine and was then applied to the DOE Reference Model 1 (not available at the start of the work) and validated with other CFD simulations such as NREL's Star CCM+ model.

Aliseda et al. created computational models for the DOE RM1, using Fluent as the software of choice and the blade element model, rotating reference frame and sliding mesh rotor implementations were used to characterize the near and far wake of these two types of turbines. Excellent results were obtained with the rotating reference frame for the DOE RM1 and with the sliding mesh for two axial flow turbines in close proximity of each other and in a highly sheared ambient flow. The accuracy of the blade element model for the DOE RM1 was established as very good for the wake past the first two diameters downstream, where the rotation in the wake has decayed to less than 5% of the free stream velocity and the wake has become axisymmetric, forgetting the actual signature of the blade passage.

Wake evolution after the 2D downstream station becomes much more dependent on the modeling of the turbulence (closure model) than on the rotor implementation. Aliseda's team demonstrated that the K-omega SST is a good balance of accuracy and simplicity with the number of inputs and the ease of measuring those experimentally. The Spalart-Almaras 1-equation model, while producing excellent results on the rotor blades, as evidenced by the coefficient of performance (C_P) predictions on the NREL Phase VI rotor, did not correctly predict the wake evolution. Similarly, the K-epsilon model can predict the wake evolution accurately if the momentum deficit is adequately input into the simulations to create the wake, but the power extraction was not well resolved due to inaccuracy of the flow simulation on the blade surface (or through the rotor disk in BEM). As a result both of these models did not produce accurate predictions for power, torque, thrust and wake evolution.

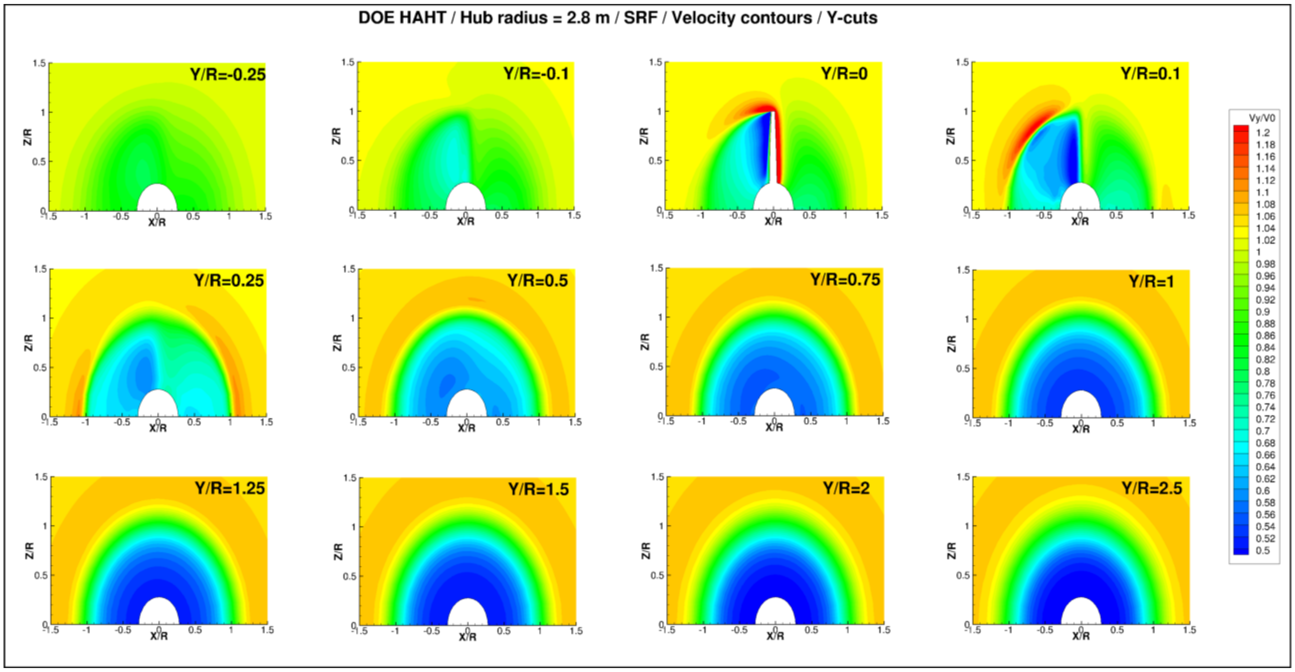

Figure 12: Streamwise velocity contours at different cross sections along the tidal channel. Notice the influence of the blade passage on the top right panels (Y/R=0 and Y/R =0.1) and the evolution of the turbine wake into an axisymmetric momentum deficit profile at Y/R=1-2.

These models are available in all major commercial computational fluid dynamics codes and can be implemented and used to analyze specific turbine designs in a manner that is consistent with the rapid design evolution of the MHK industry. The models range from highly detailed simulations that can predict the structural stresses and vibrations on a MHK turbine blade, to the simplified descriptions that can reproduce the physics of the energy extraction and subsequent wake in large arrays. Hence these models enable the design of turbine arrays (up to 100s of turbines) and allow for the analysis of the impact of specific turbine parameters (such as tip speed ratio, number of blades) on the performance of entire arrays.

Aliseda's and Polagye's groups have created a tandem of computational model-scaled experimental model of a cross-flow helical turbine. This generic and openly available design has been fabricated at two scales (0.2 m and 1.0 m height) and tested in a flume and in the field, towed behind an unpowered skiff, see Figure 13.

Figure 13: Cross flow helical turbine.

The torque and power predicted by the numerical simulations were compared to the experimental results. The comparison shed light over the strengths of each of the methodologies in understanding the dynamics of cross-flow MHK turbines. It also identified the challenges in using some specific results from these studies to design and quantify performance of this type of turbine. The data collected and the subsequent analysis published has started to outline a method to study the influence of solidity ratio and tip speed ratio on cross-flow turbine performance. Results from the combined simulations/experiments, although qualitative in nature, highlighted the impact of upstream blade wake on downstream blade performance, hinted at the strong influence of turbulence on rotor performance; and provided insights into wake structure and propagation. It can open the door to optimization of designs of helical cross-flow turbines by industrial and academic partners, and it can show the way to study the resulting prototypes, both through scaled-down experiments and through computation. In addition, the field-scale prototype could serve as a platform for instrumentation development (e.g., testing of fiber optic strain gauges) and technology advancement (e.g., use of Doppler sonars for feedforward control).

In addition, Aliseda's group has analyzed the effect of channel confinement on MHK turbines across a wide range of parameters. First, they demonstrated through simulation that, for most cases of interest in rivers, tidal flows and ocean currents, the Froude number traditionally used in hydraulics is irrelevant to the flow field and performance of MHK turbines. There are two non-dimensional parameters that represent the influence of the free surface on MHK turbines. The turbine diameter and the turbine depth are the key parameters, not the channel depth (see Figure 14). Thus, the important non-dimensional values that need to be taken into account to understand the influence of the presence of a free surface on MHK turbines are the turbine diameter Froude number and the depth to diameter ratio. The second key result from this study is that the performance dependency on turbine/channel blockage ratio is extremely complex and cannot be accounted for with just geometrical or thrust coefficient corrections such as Glauert's classical correction for wind tunnel aerodynamics. They explored the performance of MHK turbines in high blockage ratio channels at constant tip speed ratio and found the improvement of the power coefficient to be significant, exceeding the Betz limit, but much lower than predicted in the literature. Further analysis helped to identify the limitations in existing computations of high blockage ratio prediction that maintain a theoretical optimum induction factor that greatly exceeds realistic values. Two lessons are learned from this: the increase in performance due to high blockage ratio is important and must be accounted for in order to use data from experiments to assess MHK technology; and the possibility of creating

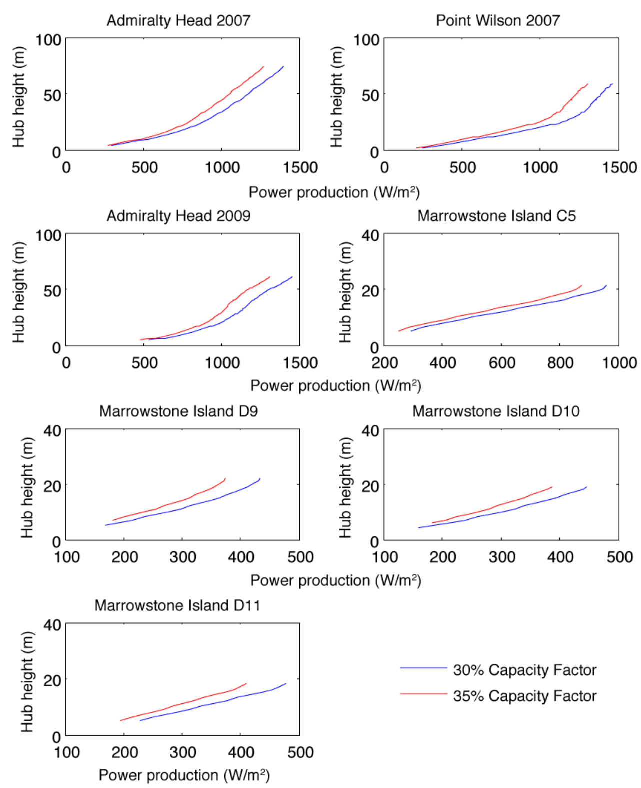

Figure 14: Power production from hypothetical 10m turbine placed in various Admiralty Inlet locations.

high performance MHK turbines to operate in highly constrained environments requires an entirely new design paradigm away from existing designs of sparse arrays of MHK turbines.

Fabien's group focused on the development of efficient methods to determine the equilibrium configuration of slack moored tidal turbines. In simulation, the submerged body and mooring lines are subject to various loads including: gravity, buoyancy, viscous drag due to a constant stream flow, applied forces and applied torques. The elastic mooring lines in the system can only support tensile loads, and are arranged in a network so that some mooring lines may be completely slack. A Lagrangian mechanics framework to determine the equations of equilibrium of the system.

A 3-turbine lab-scale array was designed, built, and tested for the DOE RM1. Experiments were conducted on these lab-scale model arrays with torque, power and wake characterization via torque cell, angular encoder and particle image velocimetry measurements. The UW flume, with a test cross section of 0.6 x 0.6 m^2 and a peak velocity of 0.7 m/s, was used for the testing of the helical cross flow turbine. The Bamfield Marine Science Station flume, with a 1 x 1 m^2 and a peak velocity of 1.25 m/s, was used for the experiments with the DOE RM 1 lab-scale turbine. Detailed measurements of wake velocity were taken at 2, 3, 5, 7, and 14 diameters downstream of the turbine rotor. This data was used to inform a variety of turbine implementations and turbulent closure models in the CFD simulations. For the Horizontal Axis Hydrokinetic Turbine, the rotating reference frame produced excellent results in the prediction of turbine power extraction and wake development, as long as the K-omega SST turbulence closure model was used for the entire simulation (flow around blades and in the wake). Blade Element model simulations also produced good results, with the K-omega SST closure, and these results improved significantly when 3D CFD simulations were used to compute the lift and drag coefficients for the correct Reynolds number at which the rotor is operating, rather obtaining these coefficients from 2D simulations or experiments at Reynolds numbers available in the literature. Additionally, LES and Particle-Vortex Method simulations were used to obtain high fidelity simulations of the turbulent flow around the turbine rotor. These methods were useful to obtain insights into the physics of the turbulent wake evolution but represent a prohibitive computational cost to simulate even lab-scale (not to speak of field scale) turbines and their wakes. Thus, those are research tools to understand the complex hydrodynamics in complex arrangements such a highly constrained flume experiments, or field deployments in highly sheared currents or under complex bathymetry, but cannot be used for design engineering.

Rules on optimum turbine spacing given constraints on area occupied by the array, number of turbines in the array and blockage ratio in the channel, were developed from the simulations, with the input from the experiments introduced in the validation and verification stage. Additionally, optimum TSR schedules for the different rows were developed to optimize the array power extraction.

Lastly under this task, Fabien's group focused on the development of efficient methods to determine the equilibrium configuration of slack moored tidal turbines. In simulation, the submerged body and mooring lines are subject to various loads including: gravity, buoyancy, viscous drag due to a constant stream flow, applied forces and applied torques. The elastic mooring lines in the system can only support tensile loads, and are arranged in a network so that some mooring lines may be completely slack. A Lagrangian mechanics framework to determine the equations of equilibrium of the system.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

The first difficulty was related to the fact that there was no accessible information about MHK turbine designs to use in the study. This was solved by the DOE Reference Models, specifically RM1 which we worked on extensively, but for the first two years of the project, we worked on a completely device-neutral simulation methodology that we validated with data from the NREL Phase VI wind turbine that fell in the right range of Reynolds number and Tip Speed Ratio for Marine Hydrokinetic Turbines. Once the DOE RM1 became available, we were ready to work on it immediately and produced simulations of single rotor hydrodynamics that compared very well against the full rotor sliding mesh simulation from Michael Lawson at NREL. Additionally, we started working on a lab-scale version of the DOE RM1 for experimental validation. The strong Reynolds number dependency of the NACA 63 family airfoil used in the DOE RM1 design, optimized to minimize cavitation at full scale, resulted in very poor performance for the lab-scale. This is a common problem that plagues lab-scale testing of MHK devices, as the chord-based Reynolds numbers are always in the 50,000-100,000 for large scale lab flumes. The SAFL study of the DOE RM1 ran into the exact same problem. To circumvent this challenge, we designed an entirely new rotor that used a low Reynolds number laminar separation bubble so that it would operate above that critical behavior at the flume scale. The strategy for this design was to match the same Cp-TSR curve of the DOE RM1 at full scale. This was different, and complementary, to the SAFL strategy to maximize chord length to maximize chord-based Reynolds number. It resulted in a blade with low solidity ratio that reached peak power at TSR=7.15 and therefore reached very high Reynolds numbers (above 100,000 for almost the entire span of the blade) despite its short chord length. Thus, we managed to have a laboratory scale rotor that matched the performance curve of the RM1 at a high enough Reynolds number to be independent of it. We built three of these fully-equipped turbines and tested the 3-turbine array at a variety of configurations and speeds.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The team developed a simulation methodology to study the influence of confinement on turbine performance, and the influence of turbines on flow redirection in estuaries. Additionally, the team developed an experimental capability to design, build and test lab-scale turbines, single or small arrays, in large flumes. The objective of creating the know-how to distribute the turbines in an array along an estuary to optimize performance and to simulate the impact of turbine arrays on flow redirection, as well as on the physical environment experienced by small animals or sediment particles that flow through the array, was achieved. Experimental validation was completed with laboratory experiments. In the absence of full scale deployment of pilot-project laboratory experiments had to be developed, including a lab-scale fully-instrumented turbine representative of full scale performance. Spacing rules that were originally formulated from computational simulations were validated by flume experiments in small arrays were two and three rows of turbines were represented. This had the indirect effect of starting an effort to understand how high blockage, intrinsically associated with flume testing of single turbines and small arrays (the turbine rotor is always designed to push the envelope of what can be fitted inside the flume cross section, and the array spacing configurations to be tested are also on the verge of the maximum distances between turbines possible inside the flume), affects the performance and wake development of MHK turbines.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and related references for this research objective are described in detail in in Appendix B.

COLLABORATION/OPTIMIZATION WITH MARINE RENEWABLE AND OTHER RENEWABLE ENERGY RESOURCES (TASKS 3, 9, 15)

ORIGINAL HYPOTHESES OR SCOPE

These tasks were originally intended to leverage the existing expertise and knowledge at NREL, nationally, and internationally that can be used synergistically to accelerate the development and large-scale deployment of reliable, cost competitive hydrokinetic renewable energy technologies.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

To support the establishment of open-water test facilities for marine and hydrokinetic technologies, NREL collaborated with NNMREC to create a draft guidelines document for testing wave energy converters at sea, including pre-deployment readiness assessment and preparation. The document aims to provide a comprehensive set of wave energy system testing guidelines to assist in developing test plans that help reduce risk and maximize safety for successful open-water testing. The protocols describe practical testing methods that can be followed to systematically identify design deficiencies at the earliest stage possible when it is least expensive to repair and to ultimately demonstrate device performance in real sea conditions. Technical standards and industry best practices serve as the basis for these guidelines and where standards and other protocols are available; this effort references them. When no standard is available with detailed performance measurement methods, this document goes into greater detail to fill in the gap. In this way, this protocols document acts as an over-arching structure, utilizing both existing standards and newly developed protocols to create a comprehensive resource.

NREL leveraged decades of experience with establishing and operating the National Wind Technology Center and knowledge of renewable energy (e.g. wind energy) technology research and development to provide feedback and guidance to NNMREC in the establishment of the wave energy test center and the development of documents listed below. In particular, they provided NNMREC with:

- Wave Energy Test Protocols and an example Generic Wave Energy Test Plan
- Information on NWTC operations, agreements, environmental health and safety considerations, costs and cost recovery
- Guidance on establishing and maintaining testing accreditation
- Examples of NREL documents for: Risk evaluation, Job Hazard Analysis, testing agreements, General Safe Operating Procedures

Moreover, NREL supplied NNMREC with standard NREL Cooperative Research and Development Agreements and Technical Services Agreements. NREL also focused effort toward supporting the design of the Ocean Sentinel (also referred to as the Mobile Ocean Test Berth in documents), leveraging NREL experience with energy device testing and marine data collection.

In addition to NREL’s work, a great deal of effort at OSU was put into tools that produce high time-resolution data that can be utilized for grid integration studies. This data was then used to determine how wave power impacts reserve requirements, which are a key metric for understanding variability and interaction between renewable sources. In Parkinson (2015), reserve requirement analysis was used to demonstrate that wave power would likely be cheaper to integrate than wind power. It is shown that integration of 500 MW of wave power will cost $1 per kW, approximately an order of magnitude less than wind power (see Figure 15).

Halamay and Brekken show how wave power interacts with solar and wind. Figure 16 (from Halamay and Brekken (2011a)) shows that a reduced WEC model can easily accommodate up to 30% wind power penetration along with 5% wave power penetration, but larger amounts of solar penetration causes transmission line violations when combine with wave power.

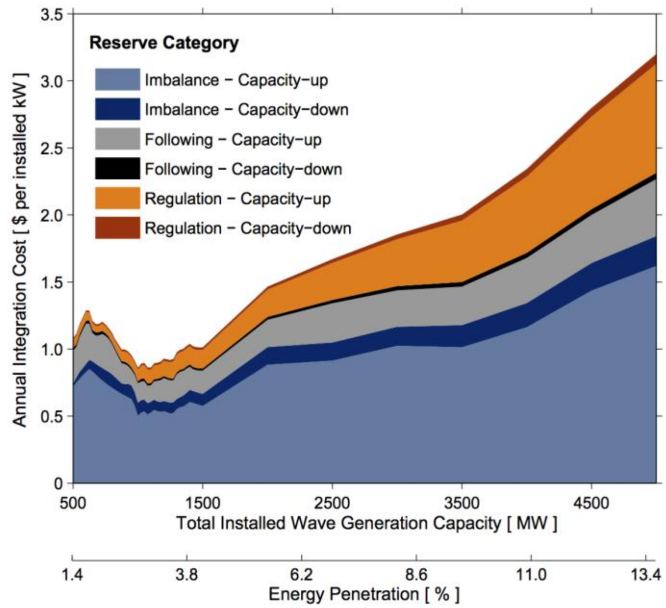

Figure 15: Integration cost of wave power

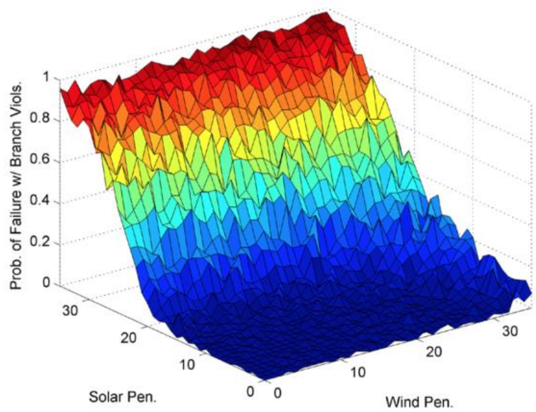

Figure 16: Test system probability of failure as a function of solar and wind power penetration for 5 percent wind penetration.

Lastly, as depicted in Figure 17, Halamay and Brekken (2011b) show the impact on reserve requirements for systems with wave, wind, and solar generation. It is shown that diverse systems tend to have fewer reserve requirements per penetration than systems without diversified renewable power portfolios.

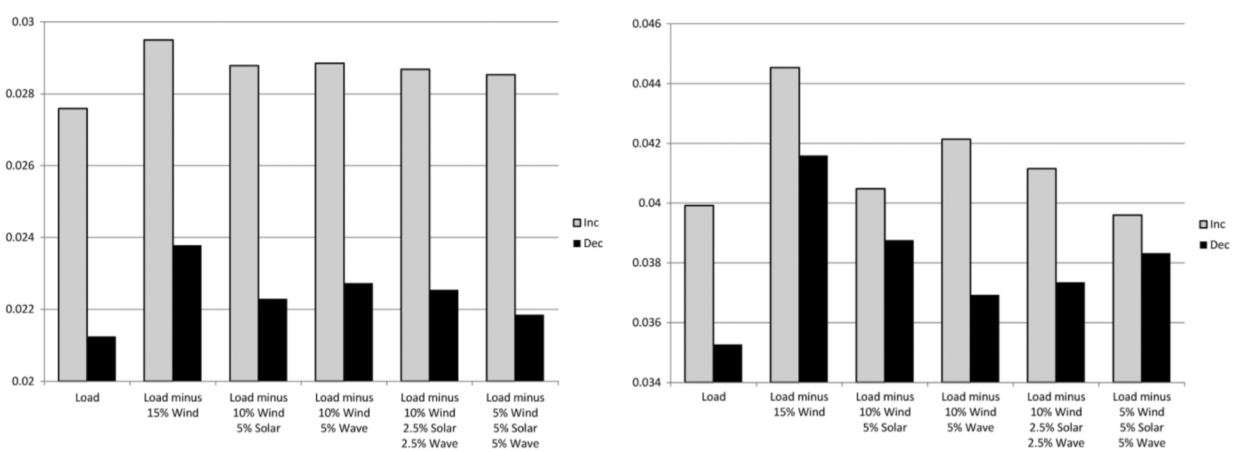

Figure 17: A diversified power portfolio tends to decrease reserve requirements.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

No problems were encountered.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

There was a deliverable for Task 9.1 to deliver a report documenting the potential of hybrid renewable systems to accelerate deployment and development of economies of scale. NREL did not write this report, instead focusing efforts on the Ocean Sentinel development.

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DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in in Appendix C.

INTEGRATED AND STANDARDIZED TEST FACILITY DEVELOPMENT – WAVE ENERGY (TASKS 4.1, 10.1, 16.1)

ORIGINAL HYPOTHESES OR SCOPE

A significant part of NNMREC's mission is to facilitate the commercialization of marine energy technologies. To fulfill this mission aspect NNMREC has as one of its objectives, to develop ocean test facilities that can be used by WEC developers to test their prototypes. The original intent of these tasks was to develop a full-scale mobile ocean test berth to test WECs including power analysis & data acquisition (PADA) modules and load bank modules. Further, planning around a multiple-berth grid connected test facility was to begin.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

Scaled Testing

While developing the capacity for standardized ocean testing, NNMREC has served developers' testing needs through the O. H. Hinsdale wave tanks. These tanks provide two options for developers as they advance their device designs to test scaled prototype tests. The first, the Large Wave Flume (shown in Figure 18) is equipped with a large-stroke, piston-type wave-maker capable of generating unidirectional waves to simulate tsunamis, hurricane waves and coastal storms. It accommodates roughly 1:10 to 1:30 scale devices. NNMREC has assisted in testing several Columbia Power Technologies devices, and the M3 Wave device in this tank, along with a research AWEC discussed previously. The Hinsdale Lab's Directional Wave Basin (shown in Figure 19) provides an opportunity to test devices under realistic scaled scenarios, with a multi-segmented piston-type wave-maker capable of generating multidirectional waves. Developers including Columbia Power Technologies, M3 Wave, Wave Energy Technology New Zealand and Neptune Wave Power have tested in this tank. The Directional Wave Basin is appropriate for both single devices and arrays and accommodates devices in the 1:33 to 1:100 scale range.

Figure 18: OSU's Large Wave Flume

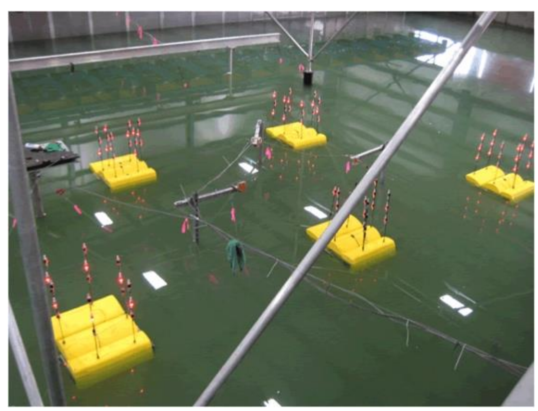

Figure 19: OSU's Directional Wave Basin with five Columbia Power WECs under test.

Ocean Testing

Figure 20: NNMREC's Mobile Ocean Test Berth Instrumentation Buoy, the Ocean Sentinel

One of NNMREC's major accomplishments, supported by the initial round of DOE funding, congressionally directed projects, state funding and other non-federal funding cost match, is the permitted Pacific Marine Center North Energy Test Site (PMEC-NETS) located two miles offshore, in Newport, OR. Another significant accomplishment, supported by the same funding sources, was the design and construction of the mobile ocean test berth, the Ocean Sentinel instrumentation buoy, for use at that test site. The Ocean Sentinel, shown in Figure 20, was completed in 2012 and is based on a NOAA NOMAD buoy platform; it facilitates open-ocean, stand-alone testing of WECs with average power outputs of up to 100 kW.

The Ocean Sentinel was deployed for the first time in August 2012 to test an experimental half-scale WET-NZ WEC. The Ocean Sentinel and WET-NZ were moored at NETS for a six-week period while the testing was performed. The tests realized a number of objectives, as follows:

- To deploy a half-scale WET-NZ in open ocean for the first time in US waters, demonstrate and characterize the WEC;
- To demonstrate Ocean Sentinel operation, and to gain experience testing a WEC with the Ocean Sentinel;
- To gain experience deploying both the Ocean Sentinel and a WEC in the ocean;
- To perform environmental monitoring during ocean testing of a WEC.

The Ocean Sentinel performed as designed throughout its first deployment, and the ability of the power converter together with the CompactRIO control and data acquisition to control the WET-NZ generator load and collect data proved to be very effective for evaluating WEC performance. The design and development of the Ocean Sentinel and the results of the WET-NZ testing are presented in Lettenmeier (2013) and von Jouanne et al. (2013a), (2013b).

The Ocean Sentinel anchors/moorings were deployed along with the corner marker buoys in mid-August. The Ocean Sentinel was then towed from the Toledo Boatyard to OSU's Ship Operations at the pier near the Hatfield Marine Science Center in Newport. The Ocean Sentinel along with a TRIAXYS wave monitoring buoy (see Figure 21) which measures wave magnitude, period, direction, and currents, were deployed using the OSU research vessel, the *Pacific Storm*. The WET-NZ anchors and moorings were then deployed, followed by the WET-NZ itself along with the umbilical cable to connect to the Ocean Sentinel.

Figure 21: TRIAXYS Directional Wave Measurement Buoy

The WET-NZ was tested using the Ocean Sentinel (see Figure 22) for 6 weeks, under varying load and time period specifications, which allowed WEC performance to be characterized while operating in several different control regimes and under a variety of sea conditions. Removal of the system began with the Ocean Sentinel and ended in early October with the WET-NZ.

Figure 22: WET-NZ (foreground) testing at NETS site with Ocean Sentinel (background)

Note that with the three-point mooring system used with the Ocean Sentinel to prevent twisting and overextension of the umbilical cable, the testing window for wave energy testing at PMEC-NETS is May - October. If no umbilical cable is connected, the Ocean Sentinel/NOMAD can use a single-point mooring that can be deployed all months of the year, e.g., for environmental testing.

The execution of the ocean testing program at PMEC-NETS represents a significant step forward both for NNMREC and the wave energy industry. The challenges of ocean WEC testing span broadly across multi-disciplinary fields and organizational boundaries. Through experiences in this first test, NNMREC has developed a framework of requirements for future testing activities that will be critical to support the needs of emerging MHK technologies. NNMREC will apply the lessons learned from its ocean testing successes to the development of PMEC-SETS in order to ensure the facility will provide the fundamental needs for the future of the industry.

The development of a supporting administrative framework for NNMREC activities was equally critical to physical infrastructure, including permitting, monitoring, testing and emergency planning, insurance and contractual elements. NNMREC successfully developed the value chain for the wave energy ocean testing process, including staging, commissioning, deployment, operation, recovery, and decommissioning of the equipment. This value chain required the development of critical team members, supporting facilities and services, and the excellent relationships with the community.

While not part of initial plans, NNMREC has recognized developer interest in testing in intermediate scaled open water environments available near the University of Washington, and has supported two such tests. After testing in the Hinsdale wave tanks, Columbia Power Technologies went to Puget Sound in February 2011 to test a 1:7 scale device under intermediate scale wave conditions. NNMREC assisted in preparing for the test, and NNMREC faculty at UW engaged in acoustic monitoring for the WEC. Based on this experience, NNMREC has expanded wave energy test support to developers wishing to test in Puget Sound, and to developers testing in Lake Washington.

NNMREC also deployed the Ocean Sentinel in July 2013 for a nine-week period to perform much needed mooring analysis and testing, which included numerical modeling and experimental validation. The intent of this testing and analysis was to enable the refinement of numerical mooring models, contributing to more accurate modeling, and improved designs, of wave energy device mooring systems. During the mooring design process, the Ocean Sentinel mooring system was modeled and tested using the OrcaFlex numerical hydrodynamic modeling tool.

For the 2013 deployment, the Ocean Sentinel was configured in a three-point mooring system with load cells integrated into each mooring line (see Figure 23), where all tension loads were recorded. In addition, a TRIAXYS surface wave measurement buoy and a seafloor mounted Nortek Acoustic Wave and Current (AWAC) profiler both measured wave and ocean current data near the Ocean Sentinel. Note that the two wave and current measurement systems were deployed to enable redundancy/verification. After deployment, the recorded wave and current data is coupled with the OrcaFlex model to simulate the deployed conditions. Model predictions of the mooring line loads are compared with actual experimental loads experienced during the summer 2013 deployment, and the sources of error, uncertainties, and data correlation, as well as opportunities for numerical mooring model refinements are discussed in this report under Task 22.3 (see Baker et al. (2014a), (2014b)).

Figure 23: Ocean Sentinel mooring system with load cells integrated into each mooring line with: (left) one load cell installed on each stern mooring line where the orange swivels are used to reduce torsional forces on the load cells, and (right) two load cells used on the bow line for redundancy (not serviceable during deployment)

Results from the TRIAXYS wave monitoring buoy along with the WEC testing at the PMEC-NETS demonstration site in the summer of 2012 are described in Lettenmaier (2013).

In addition, the TRIAXYS buoy measured wave data near the Ocean Sentinel at the NETS during the summer 2013 deployment with the load cells. Figure 24 shows the Probability Mass Function (PMF) of the significant wave height for the duration of the 2-month deployment; the graph shows that significant wave heights between 0.7 m and 2 m are the most likely to occur during those summer months. Figure 25 displays the PMF for wave period where it can be seen that no wave periods of less than approximately 6 seconds were recorded, with the most likely period being between 6 and 10 seconds. Figure 26 shows the significant wave height (averaged over 20 minute intervals) for the duration of the deployment. For the majority of the deployment, significant wave heights ranged in the expected summertime levels, i.e., between 1m and 2m. However, towards the end of the deployment early storms occurred, leading to significantly elevated wave heights.

To better understand the wave resource potential of the site, the power output of a WEC installation at the site was simulated and the time series plot is shown in Figure 26. The simulated array had 400 devices arranged in a 5 x 80 grid, where each WEC was rated at 250 kW, with capacity factors of 0.5. It was assumed that each WEC is able to operate without interfering with the other WECs. A linear model for an oscillating body WEC was used, and a Power Take Off model was applied to the outputs of the linear model. Since no interference between WECs was assumed, the array power is the sum of each individual WEC's power.

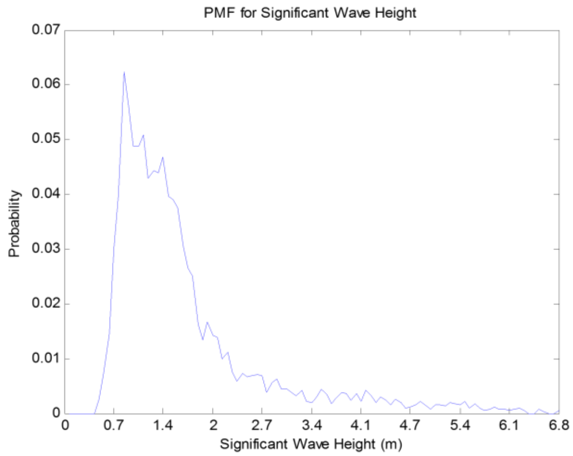

Figure 24: Probability Mass Function (PMF) of significant wave height.

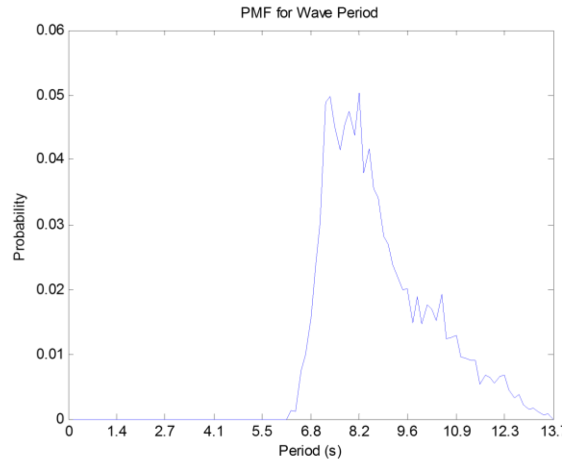

Figure 25: Probability Mass Function (PMF) of wave period.

The storms that occurred at the end of the deployment were uncharacteristic of standard summer wave conditions. For the majority of the deployment, the simulated WEC farm consistently produced above 30 MW in summertime conditions. In the stormy conditions, more characteristic for winter weather, the power output of the WEC farm increased significantly, and the average power produced over the deployment was 49 MW.

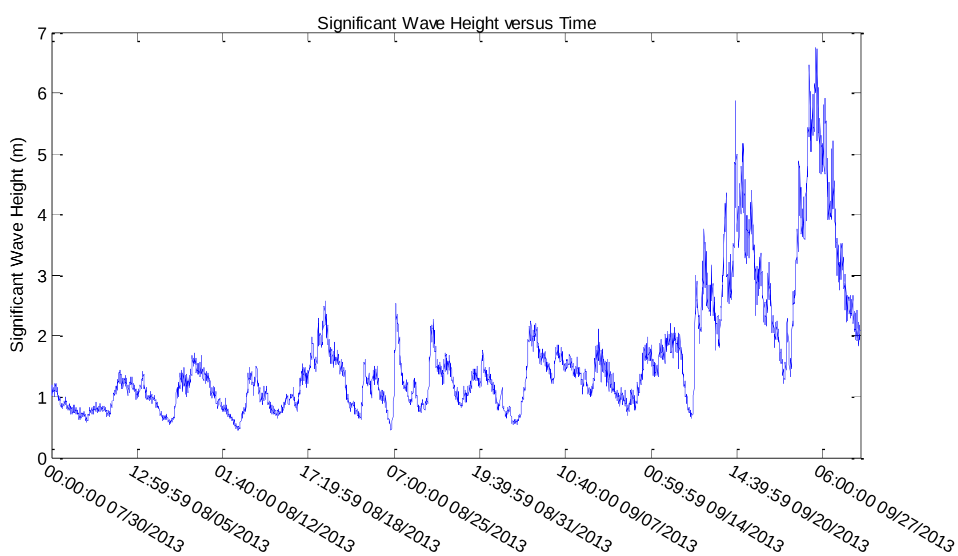

Figure 26: Significant wave height for duration of deployment.

NNMREC also collected data from TRIAXYS buoys at the proposed grid connected site, PMEC-SETS, through the end of Dec. 2015. These results are described under Task 21.2.

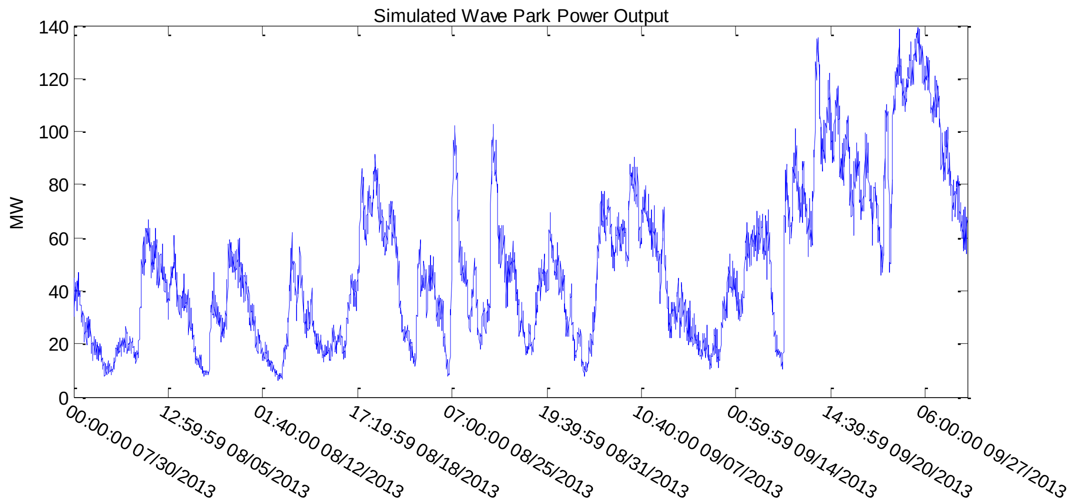

Figure 27: Power time series of simulated WEC installation at PMEC-NETS deployment location.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

Original project plans included collecting remote sensing observations of devices under ocean testing. However, since only single devices were deployed at PMEC-NETS, and only during mild summer conditions, there was not a good opportunity for this type of data collection. Hence, remote sensing efforts focused on existing laboratory data.

Late in the project, radar observations were collected at the PMEC-SETS site during a deployment of the TRIAXYS buoy. This work was leveraged with a separate DOE funded project.

In 2005, OSU began engaging the community of Newport, OR, to propose a wave energy testing facility in a cable-to-shore configuration. At that time concerns were expressed regarding the invasiveness of the cable-to-shore before successful demonstration of wave energy testing, and before the industry benefits and needs were better understood. Therefore, in 2006 (before NNMREC), von Jouanne and team proposed the concept of a floating Mobile Ocean Test Berth (MOTB) as a temporary, reduced-impact wave energy testing facility. In 2007, OSU was awarded $3M of funding from the Oregon Legislature toward the design and construction of the MOTB. With the establishment of NNMREC in September 2008, OSU sent the MOTB concept out for bid. In 2009, SAIC was selected as the contracting company, and the pre-design began in January 2010. Nine months later, a pre-design for a 500 kW floating MOTB was completed. Unfortunately, due to the grid mimic challenges at 500 kW, and the size and flexibility characteristics of the power cable from the floating MOTB to the WEC under test, challenges remained to find a solution for stability and survivability issues. After review of the challenges associated with the design, installation, and costs of the MOTB at the 500 kW scale, NNMREC determined it was prudent to reconsider the MOTB scale and design process. Thus, NNMREC assembled a group of outside experts to review the alternatives (and components of the alternatives) and provide expert feedback to consider in planning the path forward. The expert review team recommended that NNMREC pursue a phased test facility process toward a cable-to-shore based test berth, with Phase 1 as follows:

- Phase 1a: Developed a permitted open ocean test site
- Phase 1b: Developed testing protocols for open ocean testing
- Phase 1c: Built a 30 kW Power Analysis and Data Acquisition (PADA) system for operation from on vessels, and a 100kW stand-alone Instrumentation Buoy, which became the Ocean Sentinel. Phase 1 was completed and branded as PMEC-NETS (Pacific Marine Energy Center North Energy Test Site).

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

Routine radar collections were not performed, for the reason described above. Fairly routine in situ deployments were conducted; these data are a deliverable.

The Ocean Sentinel has proved to be very effective for evaluating WEC performance. The electrical data acquisition and data processing facilities built into the Ocean Sentinel combined with data transfer to shore and the ability to deploy experiments yield a lasting and extremely powerful platform to aid the development of ocean energy technologies. A significant lesson learned, and recommendation for future Ocean Sentinel deployments includes at least 1 year-in-advance deployment planning to prevent tight deployment timeframes.

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DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix D.

INTEGRATED AND STANDARDIZED TEST FACILITY DEVELOPMENT – TIDAL ENERGY (TASKS 4.2, 10.2, 16.2)

ORIGINAL HYPOTHESES OR SCOPE

The intent of these tasks was to develop and apply of a modular and scalable instrumentation package for cost-effective performance and environmental monitoring for tidal turbines. These data would establish baseline site characteristics, inform studies of wakes, and develop design conditions for tidal turbines. Admiralty Inlet, WA was intended as the primary test site for demonstration of these techniques.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

While the tides (i.e., the change in elevation of the ocean surface) are a well-understood, deterministic process, tidal currents include both deterministic and stochastic processes referred to as turbulence. Between 2005 and 2011, a number of tidal turbine prototypes experienced structural failures, in several cases, due to an incomplete understanding of the tidal currents that they would experience in operation. Since that time, failures have become rarer, both because of increased factors of safety and an improved understanding of tidal currents. NNMREC has been at the forefront of research in the latter.

Figure 28: Initial Sea Spider deployment in April 2009.

The Sea Spider seafloor tripod shown in Figure 28 was developed through this work and, in conjunction with other projects, successfully deployed and recovered over 30 times from Admiralty Inlet, with 100% data return for tidal currents and turbulence (> 40,000 hours of bottom time). These deployments also provided critical insight into corrosion and biofouling challenges for long-term instrumentation deployments, as documented in a series of field reports. Several public data sets were produced from these deployments (see Deliverables). In addition to the processed data, methods for routine processing of tidal current (depts.washington.edu/nnmrec/characterization) and turbulence data were been published and demonstrated. Essential to these methods is the quantification of error and noise in estimating current resources and the level of turbulence. These methods were expanded to include the freely drifting 'SWIFT' platform, which expands the spatial coverage of the tripod methods. Combining short-duration turbulence data with multi-year measurements of tidal currents showed that periodic currents in Admiralty Inlet contribute ~65% of the design loads for a turbine, while turbulence contributes ~35%. Methods developed under this task informed the design conditions for the proposed, but ultimately cancelled, deployment of OpenHydro turbines in Admiralty Inlet.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

The wake turbulence study was conducted around the OPRC "RivGen" turbine in the Kvichak River, rather than an OpenHydro turbine in Admiralty Inlet. This was a necessary adaptation after the cancellation of the proposed demonstration project. The wake turbulence study used both fixed *and* drifting methodologies, rather than solely fixed measurements, and this expanded the project scope with a net benefit to the project.

The report on cost-effective monitoring options for commercial arrays was initially conceived as a stand-alone effort focused on the application of the Sea Spider platform to commercial monitoring. This activity was augmented by DOE sponsorship of an instrumentation workshop, which allowed a broader set of perspectives to be offered on environmental monitoring for wave and current projects. The resulting workshop report is comprehensive, considering the capability of fixed and drifting platforms to meet environmental monitoring needs.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

All of the original objectives were met and a wider range of methods was developed (because of the shift in locations for the wake study). The inclusion of drifting methods, in addition to fixed seafloor tripods, is an expansion of the objectives and added value to the project.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and related references for this research objective are described in detail in Appendix D.

INVESTIGATE COMPATIBILITY OF MARINE ENERGY TECHNOLOGIES WITH ENVIRONMENT, FISHERIES AND OTHER MARINE RESOURCES (TASKS 5, 11, 17)

ORIGINAL HYPOTHESES OR SCOPE

The assessment of potential environmental impacts has lagged behind the development of technology and marine energy facility siting. Construction processes and site preparation, deployment, operation, power transmission, servicing, decommissioning, the physical structures of the WEC devices and mooring systems all may have an uncertain level of impact on the marine environment and NNMREC focused on addressing these concerns.

For tidal turbine sound, the intent was to measure the sound produced by a turbine and develop a model for predicting sound detection by marine animals as a proxy for acoustic effects.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

Interactions between WECs and ocean waves result in both near-field and far-field changes in the incident wave field, including a significant decrease in wave height and a redirection of waves in the lee of the array, referred to as the wave shadow. Nearshore wave height and direction are directly related to the wave radiation stresses that drive longshore currents, rip currents and nearshore sediment transport, which suggests that significant far-field changes in the wave field due to WEC arrays could have an impact on littoral processes. Some of the goals of these tasks were to investigate the changes in nearshore wave conditions and radiation stress forcing that result from an offshore array of point-absorber type WECs using a nested SWAN model, and to determine how array size, configuration, spacing and distance from shore influence these changes.

Arrays were represented in SWAN through the external modification of the wave spectra at the device locations, based on a new experimentally determined Power Transfer Function established in an earlier WEC-array laboratory study. Twenty array configurations were simulated, including 5, 10, 25, 50 and 100 devices in two and three staggered rows in both closely spaced (three times the WEC diameter) and widely spaced (ten times the WEC diameter) arrays. Daily offshore wave spectra were obtained from a regional WAVEWATCH III hindcast for 2011, which are then propagated across the continental shelf using SWAN.

A new threshold for nearshore hydrodynamic impact due to WEC arrays was defined based on the change in the alongshore wave-driven radiation stress gradients in the lee of the array. The threshold for impact was established from a previously observed relationship between radiation stress and alongshore current magnitude found in existing field data. As an intermediate step, a parametric study was conducted to analyze the impact of a suite of WEC array designs. A range of WEC array configurations, locations, and incident wave conditions were examined and the conditions that generate alongshore gradients exceeding the impact threshold on a uniform beach were identified.

Finally, the methodology was applied to the PMEC-NETS and SETS sites to assess the applicability of the results to sites with more realistic bathymetries. For the field sites, the changes in wave height, direction, and radiation stress gradients in the lee of the array are similar to those seen in the parametric study. However, interactions between the waves in the lee an array and the real bathymetry induce additional alongshore variability in wave-induced forcing. Results indicate that array-induced changes can exceed the natural variability as much as 35-45% of the time.

A separate part of this project objective involved a team of researchers at the Hatfield Marine Science Center (HMSC) investigating the compatibility of marine technologies with the environment, fisheries, and other marine resources. They have made a number of significant contributions toward understanding potential interactions of marine energy device installations with physical and biological components of the environment. Significant accomplishments under NNMREC funding include:

1. Characterization of habitat and benthic species around PMEC-NETS and SETS;
2. Tracking of habitat changes and recovery around Ocean Sentinel anchors at PMEC-NETS;
3. Description of seabird distributions in relation to PMEC-NETS and SETS;
4. Description of gray whale migratory pathways off Newport, Oregon;
5. Tracking of marine mammal presence around PMEC-NETS and SETS;
6. Characterization of the ambient noise field at PMEC-NETS and SETS;
7. Recording of the Ocean Sentinel/WEC acoustic outputs;
8. Initial deployments of an in-house developed EMF measurement instrumentation and baseline characterization at PMEC-NETS.

From 2010 to 2013, Henkel and her team conducted environmental site characterization work at and around the PMEC-NETS site using a box corer, bottom trawl, and CTD (Task 5.1a). Physical site characterization described water quality and sediment characteristics (grain size and total organic carbon and nitrogen) across depth at the site and across seasons and years. Biological characterization consisted of identifying and enumerating organisms living within the sediment (see Figure 28), on the surface of the sediment, and bottom-associated fishes. Because this work was initiated early in the project, baseline pattern of spatial, seasonal, and inter-annual variability have been characterized. This is important for evaluating potential future project effects and has helped the industry in two ways. The first has been in potentially lowering the bar for what will be required for baseline studies for future projects. The intensive sampling conducted for the NETS and the subsequent analyses can provide information as to the spatial and temporal intensity of benthic sampling to adequately characterize future proposed installation sites. Second, establishing the range of what is "natural" allows any changes to benthic habitats or species that may be observed after installation to be put into context.

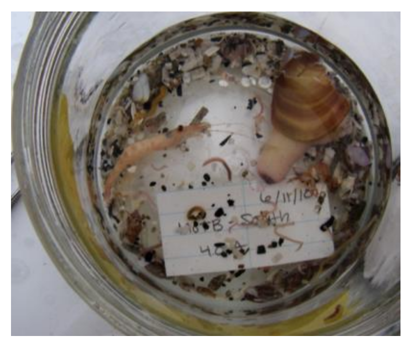

Figure 29: Infaunal organisms from a box core.

From fall 2013 (after the removal of the Ocean Sentinel) to summer 2015, in addition to continued sampling at the initially-established stations, Henkel and team collected box core samples around the Ocean Sentinel (OS) anchors to assess potential sediment and/or organism changes due to anchor deployment (Task 17.1.2). Significant changes to the sediment were detected; however, this did not result in significantly different benthic organisms collected in the "anchor grabs". The Ocean Sentinel anchors were removed in November 2015. Henkel collected box core samples in April 2016 from the anchor locations to assess recovery. This recovery assessment was supported by the Oregon Wave Energy Trust. These surveys have provided some of the first data on the actual scope (type and areal extent) of seafloor changes associated with anchor deployment and will yield the first data on post-removal recovery. This will contribute to advancement of the industry because it gives developers, regulators, and managers some bounded expectations of effects for which environmental mitigation measures can be developed.

During Phase 1, Marine Mammal Institute (MMI) teams at Hatfield Marine Science Center (HMSC) conducted surveys of gray whales migrating in the vicinity of the PMEC-NETS (Task5.1b). They described the depth and distance to shore that gray whales travel during the three phases of their migration. This work will allow researchers to determine if future WEC array installations result in deviations from the whales' migratory paths. The addition of marine mammal observers to cruises starting in 2013 has increased the observations of numbers and types of marine mammals present in the PMEC-NETS and SETS areas (another key parameter for Task 21.2.1). In Phase 2 of the project, the MMI team conducted an experiment to determine the potential effectiveness of an acoustic deterrent device that emits a sound similar to a killer whale and is intended to cause gray whales to slightly shift their swimming trajectory. If devices are not actually noisy enough for marine mammals to detect above ambient ocean noises, the deterrent device may be used in order to prevent whale encounters with WEC device components.

Also in Phase 2, Haxel conducted initial acoustic characterization of PMEC-NETS area using passive hydrophones deployed on a bottom lander (Task 11.2a). This year-long survey characterized the acoustic environment, identifying ship traffic, wind, rain, and waves crashing on the beach. It was important to quantify the noise levels of the ocean prior to any deployments in order to manage expectations about what the noise field would be like after deployment and if devices would be able to be detected above ambient conditions. Additionally, the passive acoustic hydrophones recorded low-frequency marine mammal vocalizations, allowing for identification of more species utilizing that space than visual surveys alone. Through the baseline work, Haxel determined that 10% of the recordings were above the 120 dB threshold for marine mammal harassment in the natural ocean; see Figure 30.

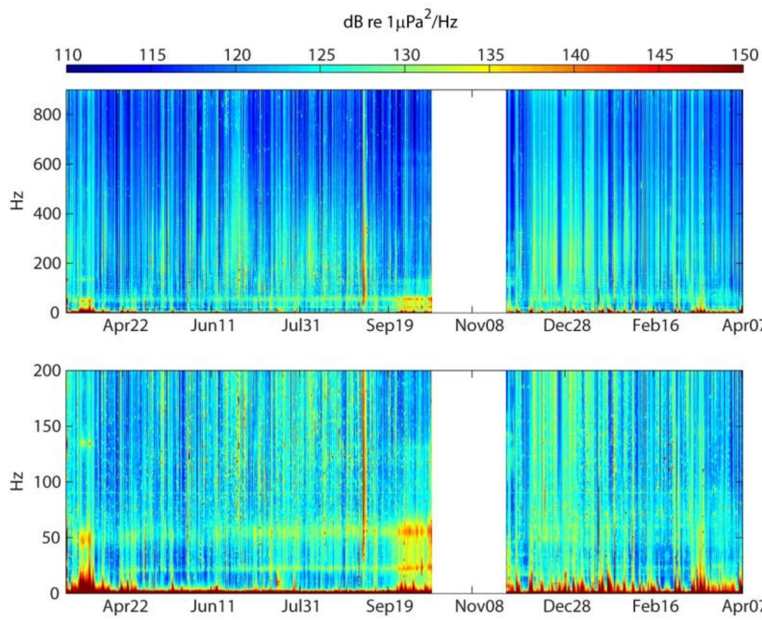

Figure 30: Acoustic data from hydrophone lander at PMEC-NETS, April 2010 – April 2011. Top: measurements from 0 – 800 Hz; Bottom: zooming in on same data, showing 0 – 200 Hz.

During the 2012 WET-NZ test, Haxel conducted an acoustic assessment of a deployed WEC and the Ocean Sentinel using towed passive hydrophones.

Monitoring electromagnetic fields (EMF) for marine renewable energy is a newly emerging application, and mission-specific instrumentation is needed. To this end, Schultz co-designed with SAIC a 1st generation EMF monitoring instrument under the support of OWET and has advanced completion of an advanced 2nd generation instrument. The 1st and 2nd generation EMF devices have nearly identical sensing capabilities, but differ in use. The 1st generation device is designed only to carry out "spot measurements" on the seafloor for short periods of time. The 2nd generation device can also carry out sustained time series observations at fixed locations on the seafloor, while accommodating higher sampling rates (4 kHz vs. 1 kHz), the addition of a seismic sensor, and a modest improvement in the magnetic field sensor noise ceiling.

Schultz conducted the first deployment series to characterize EMF at PMEC-NETS with the 1st generation EMF monitoring instrument. The EMF survey was conducted during a two-day period in mid-September using the survey vessel, *Miss Linda*. Challenges were encountered in maneuvering the survey vessel around the delicate cables and mooring lines near midpoint of the testing configuration, and the ship had considerable difficulty avoiding fouling lines or impacting the Ocean Sentinel and the WEC. This experience assisted the test team in establishing a safer standoff distance based on actual ocean surface currents at this site. Data analysis revealed that the predominant electrical and magnetic frequencies observed within the survey area were at 1Hz due to the EMF data gathering instrument itself, at 38Hz, likely due to the boat used to deploy the EMF measurement device, and 10 – 11 Hz which is yet unidentified.

Advising industry, agencies and other stakeholders on environmental effects is an on-going NNMREC activity (Task 11.2b). Henkel and Boehlert led the wave energy portion of the NOPP Protocols Framework project. Boehlert and Henkel also convened the BOEM-sponsored Environmental Effects Workshop in November 2012 (http://hmsc.oregonstate.edu/rec/). Henkel regularly gives presentations and does outreach to the public on potential environmental effects and the studies underway to address them.

In considering the environmental effects associated with tidal energy extraction, a significant hurdle to large-scale utilization of tidal energy is the uncertainty about the effects of energy removal on the marine environment. An improved understanding is need both to guarantee environmental compatibility, but also to understand how the available tidal resource will be altered by high levels of energy harvesting. Kawase's team developed a framework/checklist for local modelers to verify the fitness of their models to evaluate and quantify the extractable tidal resource and presented this at the 10th European Wave and Tidal Energy Conference (EWTEC), Aalborg, Denmark, see Kawase and Gedney (2013). This work concerns the use of numerical hydrodynamic models of regional tides for resource assessment and environmental impact assessment. Such models are now routinely implemented and run for many coastal regions and estuaries around the world; they are starting to see use in assessment of potential tidal energy resource. However, each model covers only a limited area of the ocean, and tides are imposed as boundary conditions at the ocean end. In reality, tide is an astronomical phenomenon generated at the global scale; the governing equations are elliptic in character, meaning local perturbation can alter the solution globally. This difference in physics introduces uncertainty into results of limited-domain models with tidal energy extraction represented, and conclusions drawn from them in tidal energy study.

In order to address this issue, Kawase's team constructed a highly idealized model of the ocean-estuary system, in which tides are forced astronomically and thus the system is energetically complete, i.e., the integrated energy balance has no exchange with the "outside" ocean. The first focus was to have a complete energetic account of tidal energy extraction from energy supply from astronomical sources to extraction by a tidal array; the second, to evaluate representation of this energetics in regional models of tides with a limited domain coverage.

The most significant result of the study is that, while extraction causes a tidal estuary to draw more energy from the outside ocean, a significant portion of the extracted energy comes from reduction in natural dissipation within the estuary. This means that the magnitude of naturally occurring dissipation in the estuary in an undisturbed state could influence the carrying capacity of the estuary for tidal power generation, and numerical models used for tidal energy studies should be calibrated not only for tidal range and currents, but also for energy dissipation. Tide is a source of energy for various processes that happen within an estuary, such as turbulence and mixing, and sediment transport; less energy being available to these processes as a result of tidal energy extraction would most likely make them less active.

Experiments with the subdomain models indicate that the character of the scaling relationship between the coefficient of energy extraction, amount of energy extraction and tidal range change is robust across a range of configurations, indicating that the essential character of the physics of tidal energy extraction is correctly represented in a limited domain model. However, the estimate of the maximum extractable energy does depend on the model configuration. Depending on the case studied and the model configuration, this is seen to vary by roughly ±25% around the "true" estimate made using the full-domain model. Since a portion of the extracted energy is sourced from the global ocean beyond the subdomain model boundary, and since the boundary condition for the subdomain model is not guaranteed to adapt to the changed energy flux, it is perhaps not surprising that limited domain representation introduced quantitative uncertainty into resource assessment.

A model for predicting turbine sound detection was developed using long-term pre-installation passive acoustic measurement data from Admiralty Inlet, WA and limited measurements of an OpenHydro turbine provided by the Scottish Association for Marine Science. The model was used to estimate the probability of categories of marine animals detecting OpenHydro turbine sound in Admiralty Inlet and guided the development of the final acoustic and marine mammal monitoring plans for the proposed Snohomish PUD tidal energy demonstration project, see Figure 31.

Lastly, under this project objective, the sound produced by a river current turbine (ORPC RivGen) was assessed using drifting hydrophone measurements (acoustic SWIFTs – "A-SWIFTs"). This method effectively

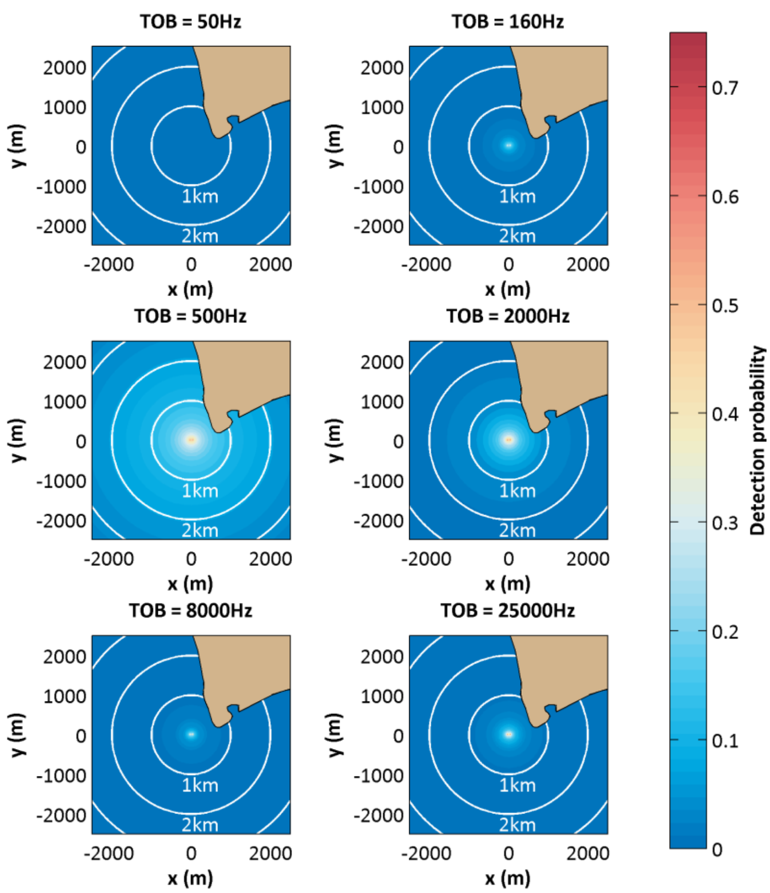

Figure 31: Probability of a mid-frequency cetacean (e.g., Southern Resident killer whale) detecting sound from a pair of OpenHydro turbines in Admiralty Inlet, WA as a function of range and sound frequency. Simulations utilized data about ambient noise, turbine sound, and tidal currents

characterized turbine sound as a function of power generation state for a given river current velocity, and the results can be seen in Figure 32.

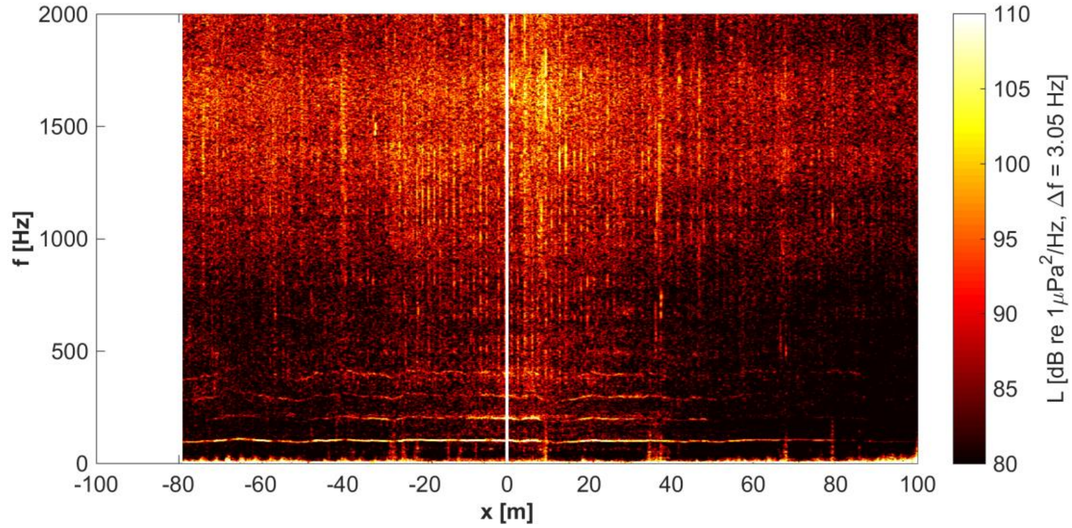

Figure 32: Drifting hydrophone measurement around the Ocean Renewable Power Company RivGen turbine as a function of distance in the along-channel direction (x < 0 denotes upstream of turbine, x > 0 denotes downstream of turbine). The continuous tonal signature apparent around 100 Hz is likely associated with the turbine generator, while the periodic broadband sound centered at 1500 Hz is caused by drive shaft misalignment (not a feature of normal operation).

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

Regarding Deliverable 5.1: Initiate marine mammal behavioral research around wave energy facilities.

Task 5.1 was rescoped as there were no wave energy facilities accessible to research during the task. Henkel added marine mammal observers to nearly all the benthic cruises to both PMEC-NETS and SETS as well as deployed the passive acoustic hydrophones and DMONs at PMEC-SETS to characterize marine mammal presence in the project area. Supported by NNMREC, the Marine Mammal Institute conducted experiments to determine the potential effectiveness of an acoustic deterrent device as described above.

Regarding Deliverables 11.1: Website and electronic document repository for environmental information; and 11.3: Annotated bibliography of environmental effects pertinent to wave energy development.

During the course of this project, a number of national and international entities launched websites and/or literature reviews focused on environmental information. Rather than produce another website and fracture readership, NNMREC partnered closely with PNNL to make their Tethys system as comprehensive as possible. Additionally, Henkel and Polagye participate in the IEA Annex IV efforts.

Regarding Deliverable 7.1.1: Workshop on EMF effects related to grid marine energy devices:

NNMREC-OSU planned and hosted a workshop (sponsored by BOEM) for all environmental effects and included EMF. Conference proceedings can be found at:

https://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/38214/BOEM-OregonMREConfProcFINAL041413.pdf?sequence=1

Multiple studies by BOEM have greatly advanced the understanding of effects of seafloor cables on the habitat and marine organisms. The greater unknown related to marine energy converters is what the magnitude and extent of EMF from the devices will be. This is something that much be measured near at-sea deployed WECs.

Regarding Deliverable 17.2.1

The model for detectability of turbine sound relied on a basic transmission loss model to estimate received levels given a source level. This was identified as a significant weakness to the method during peer review, one best addressed through parabolic equation modeling. As a consequence, the model was not publicly released, pending revisions that can incorporate more advanced models for transmission loss, or, at a minimum, contrast the difference in results obtained with transmission loss models of varying fidelity.

Regarding Deliverable 17.2.2

Originally, A-SWIFTs were planned to be used in acoustic characterization of OpenHydro turbines in Admiralty Inlet, WA. Because this project did not move ahead, the task was rescoped to a study of ORPC's RivGen turbine in Igiugig, Alaska. While the relation between current speed and received levels could not be observed, riverine measurements did allow multiple replicates of turbine sound to be recorded under varying operating conditions (i.e., tip-speed ratios) and for spatial patterns to be quantified.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

Work under this task resulted in a number of accomplishments beyond what was originally anticipated. The spatial extent covered by surveys and the range of organismal groups investigated exceeded the original expectations. Partnerships with the Oregon Wave Energy Trust and OSU's Marine Mammal Institute allowed NNMREC researchers to increase the sampling frequency of the intended tasks and to conduct focused studies on gray whales specifically. Over the course of the project, however, there was only a single 7-week deployment of a scaled WEC; thus there was no the opportunity to observe many interactions between the actual marine energy devices and marine organisms, nor did such a deployment have a detectable effect on fisheries or other marine organisms. Leaving the Ocean Sentinel anchors in the water after the 2013 deployment did give the team the opportunity to survey the effects of that component of marine energy deployments on environmental conditions of the seafloor. Additionally, the team is quantifying the biofouling on the floats and anchors to contribute to setting expectations for what might be found on deployed WECs and mooring systems when active ocean testing takes place. While there are few observations on the compatibility of marine energy converters with the marine environment, the seven years of benthic data from PMEC-NETS and two years from PMEC-SETS is invaluable for understanding the seasonal and inter-annual variability of the system in order to determine if WEC devices are having measureable effects within the range of natural variability or if they are

With regard to Deliverable 17.2.3, evaluation of tidal energetics of a regional ocean, sans turbine representation, is possible with use of a verified model, and should be considered a *de riguer* for resource and environmental impact assessment using regional ocean models. However, both numerical models of regional ocean and representation of turbine arrays in them are under ongoing development, and it appears premature to come up with a definitive checklist for developers to use for model implementation. Active research in this area is needed.

With regard to Deliverable 17.2.2, A-SWIFT measurements were successful in characterizing spatial variations in turbine sound and the relation between turbine sound and turbine operating state. No correlation was found between received levels at a position in space and power generated, but a correlation was identified between received levels and turbine rotation rate. Further, the frequency characteristics of turbine sound were observed to vary with rotation rate. These data provide insight into mechanisms for sound production by turbines and should help to bound future studies.

With regard to Deliverable 17.2.1, the attempt to model detectability of turbine sound proved useful for the proposed Snohomish PUD tidal energy project, but the empirical transmission loss model may be a weakness in extending the modeling framework to other locations and the discontinuation of that project eliminated an opportunity to validate the model's efficacy at predicting received levels.

REFERENCES CITED

Kawase, M., M. Gedney. (2013). Tidal energy extraction in an idealized ocean-fjord tidal model with astronomical forcing. *10th European Wave and Tidal Energy Conference (EWTEC)*. Aalborg, Denmark.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix E.

INCREASED RELIABILITY AND SURVIVABILITY OF MARINE POWER TECHNOLOGIES (TASKS 6, 12, 18)

ORIGINAL HYPOTHESES OR SCOPE

Marine energy devices must operate reliably and efficiently to be economically viable. One of the significant challenges for a competitive levelized cost of energy is operations and maintenance costs for a WEC array, which is hugely impacted by reliability and survivability of WECs. This project objective had two somewhat independent tracks, one that looked at survival and reliability in the wave environment with respect to the wave forces and subsequent failure or fatigue, and the second that looked at the challenges of the wave environment with respect to ocean chemistry and the effect on materials and biofouling.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

With regard to the first part of the task on the reliability and survivability in the extreme ocean environment, though there is a large body of knowledge on how waves affect large stationary structures, there is limited existing work on characterizing waves as they affect structures designed to move in the ocean, especially when those structures contain control systems that attempt to move the structure at or near resonance. Paasch's team has focused on structural and mechanical reliability and survivability of wave energy systems. This is closely coupled with his work as a technical expert on IEC TC114 PT62600-2 Design Requirements for Marine Energy Systems.

Initial work on survivability identified breaking waves as a concern for the integrity of the WEC's primary structure. Paasch's team has had several graduate students work in this area under DOE and NREL funding. While breaking waves are known to impart the most intense individual loads that offshore structures experience, they remain poorly understood in the open ocean. In particular, it is unclear how often they occur and under what conditions. Standard wave spectra exclude directionality and may not fully capture extreme events like large waves that cause fatigue damage. Analysis on time series wave data collected during large storms showed a limit to the calculated wave steepness that was fairly consistent, but whether those waves are breaking or not is unclear.

Hovland considered the impact of breaking waves on WEC design; he sought to identify and characterize breaking waves based upon the local steepness of time-domain wave records. Storms were identified in the buoy records, and return periods were calculated. The probability and severity of wave breaking were then analyzed in the context of the storms in which they were generated. The information provided by Hovland may be used to inform the design of WEC componentry that may be affected by breaking waves.

To address the lack of simulation tools, Meicke developed a virtual wave basin using Arbitrary Lagrangian-Eulerian fluid elements in the program LS-DYNA. This approach allows for the high-fidelity analysis of WEC structural response to incoming linear and non-linear waves in the time-domain. Although the method is computationally expensive, the applicability of the method should improve as computing power continues to increase. The method may provide a means for developers to analyze the response of their systems to non-linear input conditions without ever building or testing a physical prototype.

To understand survivability in the Oregon wave climate, Brown conducted a geometry independent, low-fidelity, time-domain fatigue analysis of a WEC subjected to representative conditions. The goal of this computer simulation was to develop an expected fatigue life probability distribution centered on the expected mean design life of the system. To develop the distribution of fatigue life, over 300 failures were observed, and the results are shown in Figure 33, see Brown et al. (2014). Fatigue life distributions may be used by developers and investors to predict operation expenses and risk in any environment, but this work should be particularly useful for those considering Oregon deployments.

To gather data about breaking waves and effects on WECs, Brown developed small data buoys specifically designed to detect breaking waves, and deployed them in the surf zone off the Oregon coast. He showed through analysis of field data that the acceleration "signature" of a plunging breaker in the open ocean is detectable by the buoys (see Figure 34) (Brown (2015)).

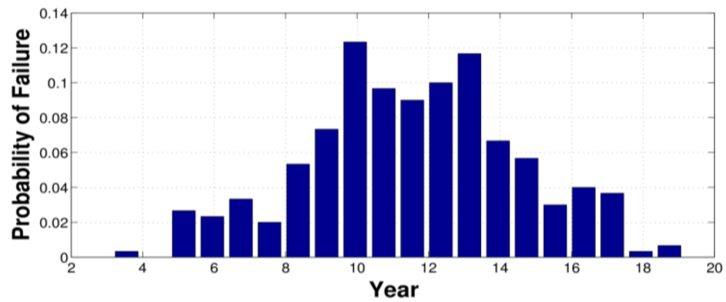

Figure 33: Probability Distribution Function of fatigue failures for a WEC PTO in a wave climate representative of PMEC-SETS; expected lifespan assumed to 12 years.

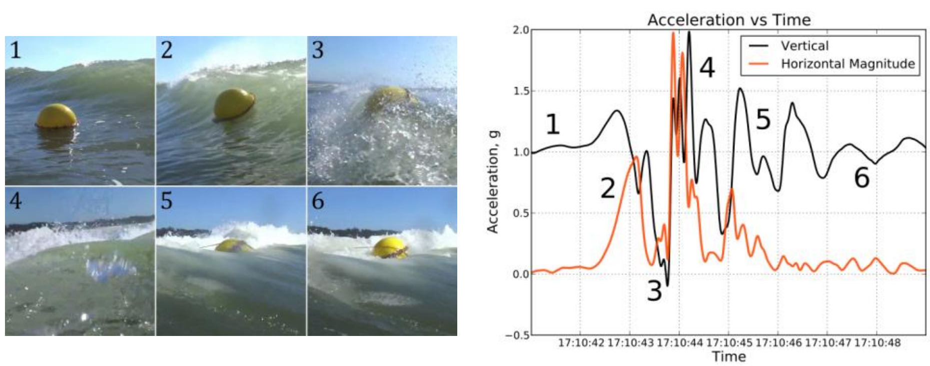

Figure 34: Acceleration signature of a plunging breaker as recorded by the data buoy.

Another area in which Paasch's team has approached reliability and survivability has been in failure analysis for power take offs (PTOs). Hydraulic PTO systems offer an attractive design solution for transforming low frequency, high force wave power into electrical power, and several developers are currently pursuing the technology. Casey, a master's student, focused on modeling and simulating point absorber WECs with hydraulic power take off systems, (Casey (2013)). In his research, two hydraulic systems were modeled: a passive system tuned to the nominal sea state, and an actively controlled system tracking an optimal power absorption velocity profile. The simulation results were used to compare the loading and power characteristics of the two systems.

The motivation for this research stems from the following observations. First, the major design objectives for WECs are to maximize power conversion while maintaining high reliability and survivability in extreme ocean conditions, as any repairs in a maritime environment will be costly. However, by maximizing power absorption, a WEC is exposed to more energetic seas and higher loadings. If the reliability and survivability of WECs is related to the nature of the loading on components, the question then arises: what are the benefits and drawbacks of a passively controlled hydraulic PTO compared to one that is actively controlled? Specifically, what are the differences in the nature of loading and power absorption between a passive and actively controlled system?

Casey's research results allow the industry to understand the characteristics of passive and actively controlled WEC systems. The analysis tools allow the developer to understand the potential design requirements of a system using high level dynamic simulations. In this way a developer can make informed decisions about which technology to pursue at an early stage in the design process.

On the biofouling aspect of this project objective, through this project, Yokochi's team determined the minimum potential required to enable electrochemical biofouling prevention of critical surfaces, and developed and validated coupled reaction/transport equations for the electrochemical biofouling prevention process. By utilizing a carbon black / graphite / polymer matrix composite that can be deployed as a conformal coating, the technology has the potential to protect odd locations in a device.

Test coupons comparing the performance of the electrochemically activated biofouling prevention coatings and that of conventional biocidal coatings were deployed from the pier and in salt water tanks at the HMSC. Results from the study show that a modest potential of about 1.1V vs. Ag|AgCl, seawater reference needs to be applied to the working electrode to achieve results similar to those for the conventional biocides, resulting in a current density of 10 $mA.m^{-2}$. Accelerated aging of electrochemical biofouling prevention coatings was measured using current density as the accelerating factor: by using the same graphite/urethane composite coatings and increasing the current density to 3.16mA/cm^2 (= 31.6A/m^2, a value limited by the electrochemical window for water since higher applied currents cause water splitting, and creates electrode damage due to mechanisms different from those postulated for the oxidation of chloride to hypochlorite), exposures equivalent to many years worth of electrocatalysis were achieved. No significant changes were observed on the exchange current density nor the charge transfer coefficient for the coatings under test.

In order to enable interpretation of the results, a series of differential equations describing electrochemical chloride oxidation at the surface of the graphite/urethane films was developed. The equations consider effects of diffusive transport of the biocide through the coating film, interfacial mass transfer resistances and advective and diffusive mass transfer through the fluid side, and computational fluid dynamics based transport series of differential equations on the seawater side, and incorporating the effects of temperature and concentration on the transport coefficients to yield a transient solution for the biocide flux and film concentration profile. Using this set of equations to extract the local concentrations of hypochlorite resulting from the measured voltages and current densities, for films of conductive paint with the impedance and electrocatalytic parameters measured shows that the surface concentration is in the order of 0.5ppm ClO^-, a value comparable with that needed to disinfect pool water.

Finally, by not releasing known chemicals with significant environmental impacts (e.g., release of Cu(II) or biocides into the environment) the electrochemical biofouling prevention technology is likely to have lower environmental impacts than biocidal coatings. This lower release of synthetic chemicals into the environment would enhance the "green" credentials of marine energy, but is only an assumption until an accurate life cycle assessment is carried out evaluating the alternatives. It appears that the electrochemical biofouling prevention technologies have the potential to be extremely useful in the development of marine energy devices, given that no depletion of active chemicals will occur in the likely lifetime of the marine energy system.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

The originally envisioned methodology for the first part of this project objective was to develop specific survivability mechanisms for WECs. However once into the project, the team realized that not enough was known about the specific environmental conditions, particularly, what events a WEC was expect to survive, to be able to develop survival mechanisms. Given this gap in understanding, the team realized that understanding the wave climate would be more useful to the industry, in fact essential, than coming up with a mechanism that would work on a single WEC. To this end, seminal work on wave resource characterization was performed; this work provided a foundation for the IEC TC114 PT 62600-101 standard on wave energy resource assessment and characterization (see Figure 35).

The major problem encountered on the second aspect of the project objective was in the assessment under actual ocean conditions, because the two attempts at using the Ocean Sentinel deployment (mounting the experiment on the hull below the water line) resulted in damage to the experiments during high seas. Therefore, real geometry performance parameters were measured in lab conditions.

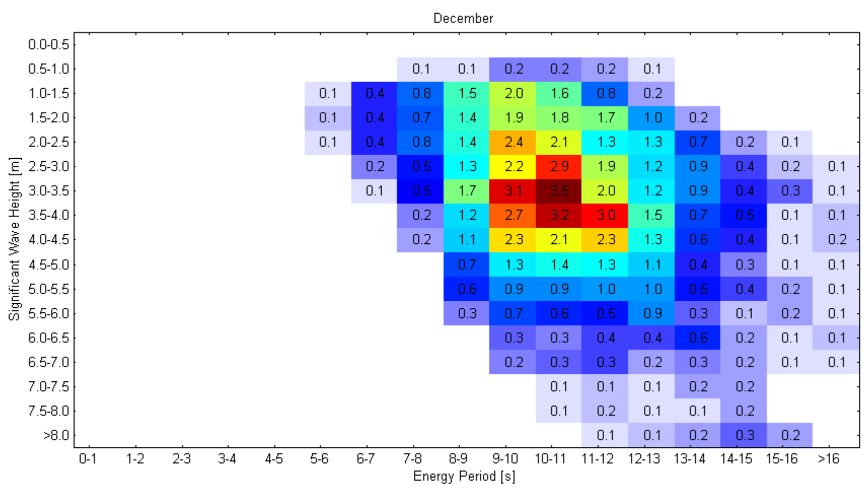

Figure 35: Wave resource characterization, providing foundation for IEC TC114 PT 62600-101 standard on wave energy resource assessment and characterization.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

Because of the redirection described above for the first part of this task, the accomplishments provide a broader and more generalizable characterization of the wave environment than was originally envisioned. The wave characterization buoy developed in house showed that identifying breaking waves was possible.

The remainder of the outcomes compared well with the planned goals, other than the problem with the damaged experiments in the high sea conditions.

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Brown A. (2015). The Effects of Ocean Variability and Breaking Waves on Wave Energy Converter Reliability and Survivability. PhD dissertation, Oregon State University. http://hdl.handle.net/1957/51393

Casey S. (2013). Modeling, Simulation, and Analysis of Two Hydraulic Power Take-off Systems for Wave Energy Conversion. Master's thesis, Oregon State University. http://hdl.handle.net/1957/40388

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix F.

SITE SELECTION AND OUTREACH (TASK 19)

ORIGINAL HYPOTHESES OR SCOPE

This task was focused on completing the site selection process for the grid connected wave energy test facility, Pacific Marine Energy Center South Energy Test Site (PMEC-SETS). Specifically, the task consisted of a more detailed analysis of four potential sites, including test site layout, sea based requirements, cable requirements, land based requirements, electrical connections, substation design, environmental planning issues and solutions, and written descriptions of potential constraints for each location. Project informational materials were to be prepared to help craft messages, including frequently asked questions and fact sheets, along with visual impact photomontages of the four sites. Outreach to and engagement with the stakeholder community for PMEC-SETS siting was to be completed under this task. This outreach was to include meetings with local communities to gather input and feedback about the feasibility of constructing PMEC-SETS in their community.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

The collaborative siting process for PMEC-SETS built upon lessons learned from the collaborative siting of the PMEC-NETS. While there are many obvious technical components of these accomplishments, there are also the societal ones. For example, executing a collaborative process for site selection, which identified and addressed stakeholder concerns early in the process rather than during the permitting process, provided a strong foundation for the collaborative permitting process executed under Task 21.

The collaborative siting process for PMEC-SETS included four different communities in Oregon and over 200 people directly. The ocean sites that were considered were selected by members of the ocean user community, many of whom are typically considered to be unsupportive of ocean energy, e.g., commercial fishermen, but who are vocal supporters of NNMREC generally and PMEC-NETS and SETS specifically. The process also created many new partnerships with local businesses, and these relationships will now be passed on to developers. The supportive nature of the selected community, Newport, is leading to a permitting process with extremely low community conflict as the outreach and engagement piece has already been heavily invested in and conflicts have been reduced. A master’s student in Marine Resource Management did an assessment of the effectiveness of the siting process. The results of that assessment can be found in Goodwin (2015).

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

No problems encountered or project rescoping along the way. The outreach and engagement in site selection led to a very successful siting of PMEC-SETS.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The accomplishments satisfied the original goals and objectives of this task.

REFERENCES CITED

Goodwin B. (2015). Evaluating Community Engagement in Wave Energy Siting off the Oregon Coast. Master's thesis, Oregon State University.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix G.

ENGINEERING STUDIES AND UNDERLYING ANALYSIS—MARKET AND SUPPLY CHAIN ANALYSIS (TASK 20.1)

ORIGINAL HYPOTHESES OR SCOPE

The Market Analysis will identify potential clients and their needs based on the current and anticipated future (next five to ten years) status of the ocean renewable energy industry. This analysis will determine whom PMEC-SETS should target and what infrastructure and services PMEC should provide. An analysis will include, but will not be limited to: a sector profile (technology and market trends, and prospects), technical requirements (construction, deployment, mooring configuration, interconnection, operations and maintenance), and services offerings of PMEC (performance monitoring and analysis, environmental monitoring and analysis, engineering support, and regulatory/permitting support). The Supply Chain Analysis will look at the availability/accessibility of products and services necessary for demonstration stage development, and the monetary costs of those products and services that must be well defined in order to identify resources and potential gaps. This task will analyze the following supply chain areas: materials suppliers, manufacturing/construction providers, transportation, assembly, deployment, operations and maintenance, emergency response, removal/decommissioning, and labor (workforce and professional services).

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

Market Analysis

The Oregon Wave Energy Trust (OWET) has worked for many years with NNMREC to support the development of the full-scale, grid-connected ocean test center for WECs that has come to be known as the Pacific Marine Energy Center South Energy Test Site (PMEC-SETS) in Oregon. The primary goal of PMEC-SETS is to advance understanding of the effects and capabilities of WECs at utility scale and small WEC arrays in order to support the industry to responsibly reap the benefits of this clean, renewable energy source.

To move forward in the development of PMEC-SETS, OWET commissioned GL Garrad Hassan America, Inc. (GL GH) to carry out a wave energy market analysis. The objective of this study is to identify potential end-users of the test center and their needs based on current and future requirements of the wave energy industry. The findings detailed in the report will inform the infrastructure design and the services offered for PMEC-SETS to be an integrated, standardized test center for wave energy developers.

GL GH approached this work in three stages:

1. Sector profile

GL GH began by analyzing the current and future prospects for wave energy. The wave energy market is dynamic, with a strong need for testing and demonstration in the next 5 to 10 years. European countries have historically been the main hubs of activity for large-scale prototype deployment, but the US market is promising in terms of feasible resource, current interest and activity, and in some cases attractive local policies. Global activity in the wave energy field over the next several years is expected to reduce costs, attract investors, and accelerate the transition from prototype testing to array planning. Growing interest from industrial players, such as major utilities or multi-national original equipment manufacturers (OEMs), in the market could also drive a step change in the rate of deployment.

2. Stakeholder consultation

Following the "big picture" analysis of the wave energy market provided in the previous section, the stakeholder consultation drilled down to the needs of potential PMEC clients in terms of technical requirements and services offered. Drawing upon its internal database, GL GH identified 37 WEC developers who are sufficiently advanced to be potential end-users of the PMEC SETS test center considering a roughly five-year timeframe. Nineteen of these developers completed GL GH's online survey, and 13 follow-up interviews were conducted.

3. Gap Analysis

Based on the results of the above two phases, GL GH conducted gap analysis that compared developers' requirements and preferences with both site conditions at the proposed location and an initial proposed technical offering for PMEC-SETS. As the general site for PMEC-SETS had already been selected, there was limited scope for NNMREC to change these conditions, but it was found that the physical conditions broadly met the needs of developers with technologies designed for offshore applications. Should NNMREC find it advantageous, there is more scope to modify its technical offering for PMEC-SETS going forward, although several of the current plans are also well matched with developer preferences.

Supply Chain Analysis

In 2012, the location for the establishment of the grid-connected wave energy test site for PMEC-SETS was announced to be off the coast of Newport, Oregon. This location sits near the existing PMEC-NETS, off-grid test site, which lies just north of Yaquina Head. These two areas, the grid-connected South Energy Test Site (SETS) and the off-grid North Energy Test Site (NETS) create the first dedicated wave energy test facility in the Pacific Northwest.

The 2014 supply chain study was undertaken by Aquatera Ltd, in collaboration with Orcades Marine Management Consultants Ltd (Orcades Marine), and Advanced Research Corporation (ARC). Aquatera and Orcades Marine are based in Orkney, Scotland and ARC is based in Newport, Oregon.

There were three primary aims of this study were to:

- examine the supply chain requirements for PMEC wave energy test facilities;
- evaluate the potential of the existing and foreseeable supply chain in Oregon to meet the identified needs; and
- outline strategies to fill any identified gaps and stimulate key enabling facilities or services.

The approach for undertaking this work was as follows: 1) generic requirements for wave energy developments established through previous work, along with recent experience from the European Marine Energy Centre (EMEC), the world's first grid-connected wave energy test site, were used to establish details of expected requirements; 2) existing supply chain data and a series of face-to-face meetings with supply chain members were examined to better understand the current and future capacity of the local supply chain; and 3) the expected requirements were correlated with existing and future capacity, and any possible gaps that may exist were identified to enable the successful testing of devices at the PMEC wave energy test sites.

As well as undertaking these tasks and presenting new information about key issues, the team also worked with existing information that had been gathered in other studies coordinated by.

A previous report commissioned by OWET, entitled "Wave Energy Infrastructure Assessment in Oregon," investigated the infrastructure and supply chain capacity in Oregon to support all forms of wave energy development including test center deployments and future commercial-type deployments.

That study catalogued many of the sites, facilities, customers, and supply chain businesses to be found across Oregon, particularly along the coast. The study was completed in 2009 before the site for SETS was chosen. The report provided a comprehensive dossier on technology specifications, port specifications, road and rail links, etc. Much of this information remained current at the time of the Aquatera work and though the 2014 study makes reference where needed to that earlier work, it differs from it in a number of ways:

- the 2014 study is specifically focused upon the needs of SETS, now firmly located off Newport,
- the scope of supply chain topics was somewhat broader in the 2014 study than was previously considered, and
- the 2014 study also sought to draw extensively upon experience in Orkney with regards to issues relating to the supply chain and test center operations.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

No major problems were encountered.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The accomplishments satisfied the original goals and objectives of this task.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and related references for this research objective are described in detail in Appendix H.

ENGINEERING STUDIES AND UNDERLYING ANALYSIS—ENGINEERING ANALYSIS AND PRE-DESIGN (TASK 20.2)

ORIGINAL HYPOTHESES OR SCOPE

Based on the site selected, this task will initially include preparing a Development Plan for PMEC-SETS at the selected site. The plan will describe the refined project purpose and objectives, project requirements, project plan (including detailed tasks, project timelines, and budget estimate), services/participants needed to complete the project, and a preliminary risk assessment. Within this task, engineering pre-design work will be conducted by a contracted Design Engineering Company to move PMEC-SETS as far toward readiness to construct as possible. Engineering activities and deliverables will be carried out or provided by the contracted Company to a stage sufficient to verify delivery periods for equipment and materials and improve the cost estimate of the facilities. The pre-design work will include land-based and sea-based infrastructure, the cable and operations.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

In 2013, at the request of NNMREC and OWET, the European Marine Energy Centre (EMEC) created three reports which together serve as the fulfillment for this deliverable.

EMEC developed a "Conceptual Design Report for PMEC Facility" outlining the preliminary physical development needs of a facility like PMEC-SETS located in Oregon. This report described, at a conceptual level, a proposed design for a test facility WECs offshore of the State of Oregon. The conceptual site would have a capacity for four wave devices. The nominal power output of each device would not exceed 1MW at peak. The power generated by the system would be around 1250kW average with variations over the day when four 1MW devices were in place.

The report was not a detailed design and was not intended to be used to purchase any equipment or materials. However, it could be used as an input to engineers for guidance on the detailed design of the electrical and communication systems following US or International standards.

Although site selection was not complete for PMEC-SETS at the time of writing, the ideas and concepts outlined in this report are relevant regardless of the particular site. The scope of this report covered the overall method and approach to development of the PMEC test facilities, the outline description of the electrical infrastructure for the test facilities, including cables; switchgear; electrical measurement; electrical substation concept; grid connection and ancillary equipment. The report also described in outline the requirements for test devices and the standards associated with them; requirements for power conditioning; requirements for grid connection and details of the measuring devices for both wave and tidal stream resources.

In addition, this report also highlighted the importance of health and safety in design and operation of the test facilities, including operations and maintenance carried out offshore for the deployment, retrieval and any in-situ maintenance of the test equipment and cables. Some suggestions for further work were also made at the end of the report. EMEC also developed a PMEC Cost Calculation Report and the Site Description for PMEC Facility. These are summarized below.

PMEC Cost Calculation Report

PMEC-SETS will be installed near Newport as it is a geographically well-suited location that had both economic and social advantages to the local area. The cost of procuring and installing sufficient infrastructure required to support a WEC test site was calculated in detail. This includes offshore subsea cables and substation and visitor center as required. The methodology of calculating the costs for these stages is explained in this report, along with any assumptions or allowances that were deemed necessary. The offshore distance that would be required is up to a water depth of 50m. The distance to this depth at Newport is 11.1km out to sea. The buildings are on a sandy location and, as stated by the Feasibility Study the ground may need improvement and or the buildings may need to rest on piles.

Site Description for PMEC Facility

A generalized conceptual layout was devised that seems suitable for PMEC-SETS. A level of flexibility exists in terms of changing the positions of the main elements, depending on the exact site and orientation that is finalized upon. Ideally the substation will be located as close to the beach as possible, this is to reduce costs of having long expensive cabling onshore. The Visitor Centre does not need to be located on the beach and can be found on more structurally stable land that can be some distance from the substation if required.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

No major problems were encountered.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The slower-than-expected progress with the PMEC-SETS development meant that the project details had not evolved to the degree necessary to warrant the detailed design and costing initially outlined in the SOPO. For example, the SOPO states "engineering pre-design work will be conducted by a contracted Design Engineering Company to move PMEC as far toward readiness to construct as possible. Engineering activities and deliverables will be carried out or provided by the contracted Company to a stage sufficient to verify delivery periods for equipment and materials and improve the cost estimate of the facilities." This level of engineering design goes beyond pre-design and can only be successfully undertaken when all project locations have been identified (and procured) including offshore test site, the final cable route and terrestrial infrastructure. It was therefore only possible for EMEC to conduct a level of pre-design analysis that was compatible with the maturity of the project description.

Similarly, costing and verifying delivery periods for equipment and materials can only be developed on an order of magnitude scale when the timeline for the construction of PMEC-SETS remains unknown

It is important to note that NNMREC has used these initial reports as the basis for significant additional costing, timeline and pre-design efforts under award number DE-EE-0006518.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and related references for this research objective are described in detail in Appendix H.

OUTREACH AND ENGAGEMENT (TASK 20.3)

ORIGINAL HYPOTHESES OR SCOPE

This task will maintain vital relationships with communities of place and of interest as NNMREC moves PMEC-SETS through the permitting processes. In order to gain long-term benefit from this task, outreach and engagement activities will be evaluated to determine best practices for future proposed projects. OWET will provide additional outreach using their current outlets and social media methods. Additional NNMREC outreach and engagement support will come from a part-time new position created to build local outreach capacity within the community chosen as the PMEC location. This person will be responsible for being the daily contact in the community and for engaging new audiences such as community colleges through OSU's open campus programs.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

Outreach and engagement has been a critical piece of NNMREC's success to date, both in collaborating with a variety of stakeholders and also in educating and being educated by the community in which marine energy is becoming a reality. These efforts have taken a variety shapes, including social dimension research by Conway and Jacobson and peer-to-peer engagement with regulators by Polagye, Batten, Hellin, Henkel, and Klure. Some of the more notable efforts include: collaborative siting of PMEC-NETS and of PMEC-SETS (discussed under Task 19.0), community engagement and company collaborations, and collaborative study plan development with NOAA's National Marine Fisheries Service (NMFS).

While community engagement takes many forms, NNMREC has an excellent vehicle for outreach at the HMSC Visitor Center. In 2012, with NNMREC's assistance, HMSC installed wave energy exhibits and wave tanks to educate the public about marine energy. There were 163,000 visitors to the Visitor Center that year and an additional 40,000 students, grades K-12. In NNMREC's pre-exhibit survey work, many visitors were not supportive of wave energy because they believed the cost to be much higher than current electricity rates. Through the creation of the exhibits and providing a way for the public to understand complex issues, NNMREC found a change in the post survey results. People now understand that wave energy is a societal choice, and the cost factor became significantly less of a barrier to it being publicly accepted.

As PMEC continues to develop and as device developers test at PMEC-NETS and SETS, NNMREC will continue its outreach and engagements efforts. Educational signs at the sites are planned in cooperation with state agencies, educational exhibits at the HMSC Visitor Center will continue, and further outreach in terms of summer classes for students are among the plans. Further, Jacobson is taking her experiences and lessons learned to Washington Sea Grant to build the outreach and engagement strength in both NNMREC institutions. To assist the range of marine scientists needing to utilize vessels out of Newport, NNMREC funded Jacobson to conduct a survey of fishermen willing to provide vessel support for marine research and testing. From this survey, 75 fishermen responded that they were willing to support such activities, and the information they provided will be a significant resource if PMEC-SETS comes online.

Polagye has engaged in a dialogue with NOAA's NMFS in order to provide information about the status and uncertainties associated with tidal energy development. Collaborative discussions with regulators from the Northwest Region and scientists from the Northwest Fisheries Science Center resulted in a set of monitoring plans from Snohomish PUD's demonstration project (acoustic, marine mammal, near-turbine, and benthic). Both NMFS and NNMREC agreed that all monitoring plans for pilot-scale projects should achieve, at a minimum, the following criteria:

1. The monitoring study should provide information about high-priority areas of uncertainty for commercial-scale installations;
2. The monitoring study methodology should have a high probability of producing information that can be scaled up to predict environmental changes at commercial scale projects (i.e., studies that will likely show "no effect" at pilot scales are of limited value);
3. Studies should be conducted in a manner that allows the methodology and results to be published in the peer reviewed literature. Both NMFS and NNMREC agreed that publication of rigorous results was the best way to make progress on environmental topics since the peer-review process provides an objective assessment of the quality and significance.

The outcome of these discussions established the basis for publications co-authored by NMFS and NNMREC researchers and is informing Henkel's development of similar monitoring plans for PMEC. This type of peer-to-peer engagement represents a best-practice for proceeding through the permitting process for pilot-scale projects, minimizes the potential for resources to be committed to low-value studies, and builds trust for future environmental assessments of commercial-scale projects.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

No problems encountered.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

Accomplishments under this task aligned with the original goals and objectives of this task.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix H.

ORIGINAL HYPOTHESES OR SCOPE

In coordination with appropriate regulatory agencies, a permitting strategy for PMEC-SETS will be delivered under this subtask. The strategy will focus on defining the most efficient and cost-effective way of securing all lease, license and permit requirements for the operation of the site by NNMREC, an independent entity or a consortium of entities; installation and operation of multiple device types; and phased development and/or array testing for some devices installed at PMEC-SETS. Based on the permitting strategy, this subtask will include conducting analysis and documentation to support permit applications. It is not clear at this time exactly what the permitting and environmental clearance process will be, however, it is anticipated that a NEPA analysis, USACE permits and a seafloor lease will be required. At a minimum, for any of these processes, an Environmental Assessment and Biological Assessment will be needed and this task is designed to move these along as much as possible to prepare for the construction of PMEC-SETS.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

The myriad regulatory and resource agencies related to the PMEC-SETS project and their purview are shown in Figure 36. To manage the variety of needs and authorities of these agencies, NNMREC developed a

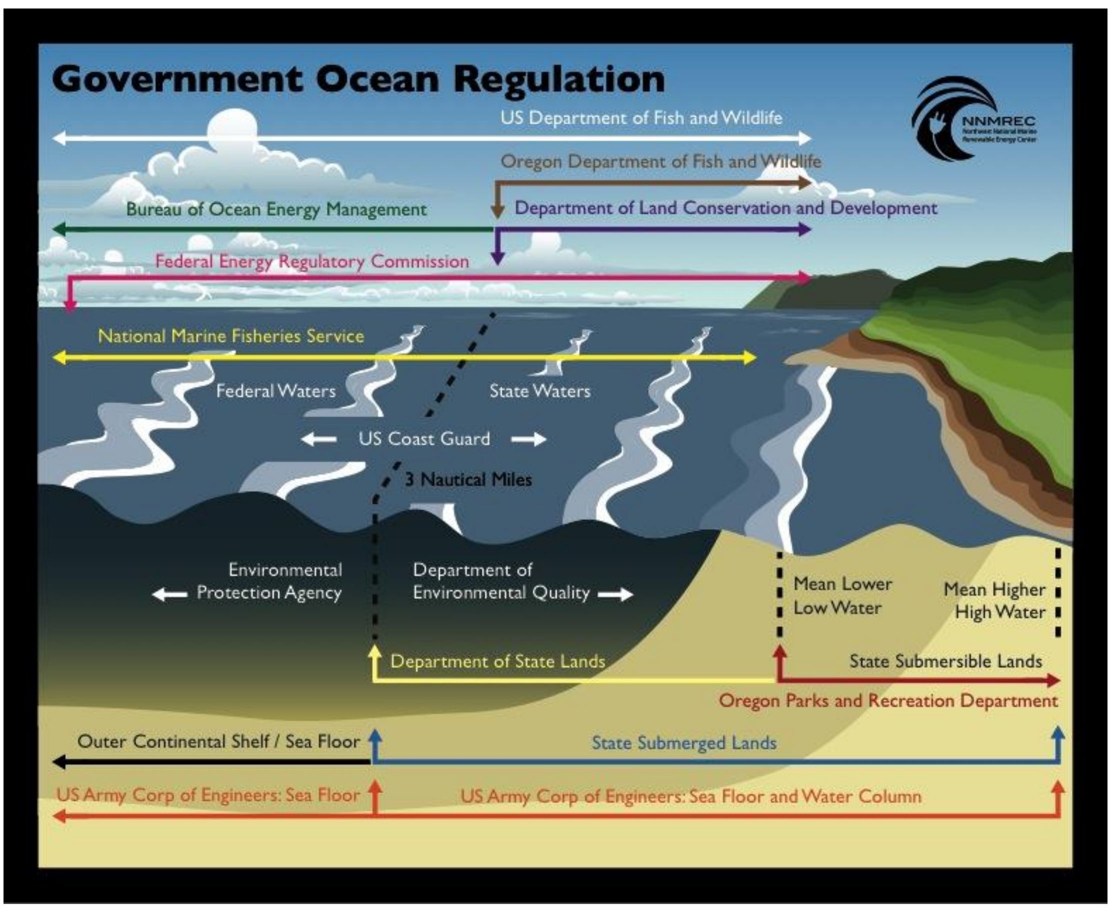

Figure 36: Federal and state agencies with authority over permitting and licensing PMEC-SETS.

permitting strategy focusing on defining the most efficient and cost-effective way of securing all lease, license and permit requirements. Initial analysis and documentation to support permit applications was completed and general approaches to developing an Environmental Assessment, Biological Assessment, and other supporting documents.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

The most difficult aspects of this task is the uncertainty associated with the regulatory process and the overall timing of engaging in a collaborative process. Although these issues did not require departure from the planned methodology at this time, they will likely be ongoing challenges moving forward.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

All the original goals and objectives of this task have been met.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and related references for this research objective are described in detail in Appendix I.

PERMITTING: SITE CHARACTERIZATION (TASK 21.2)

ORIGINAL HYPOTHESES OR SCOPE

NNMREC will conduct site characterization and collection of baseline data for electromagnetic fields, benthic characteristics and organisms, acoustics and a series of physical parameters such as wave and current measurements, bathymetry, backscatter and sub-bottom profiling. Acoustic work will be coordinated between NNMREC and HINMREC to characterize the sound produced by WECs tested by the Ocean Sentinel and Wave Energy Test Site (WETS), respectively, enabling cross-fertilization of methodologies between the two centers. A vessel traffic survey will also be conducted to understand how PMEC might impact marine traffic around the test site. Additional studies that may be required for permitting, depending on the site selected, include sea bird, marine mammal and sediment transport surveys.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

NNMREC has conducted extensive long-term studies in and around the PMEC-SETS location. Site characterization is closely tied to the permitting process for a test site such as PMEC-SETS. Agency and stakeholder involvement is critical in defining the pertinent issues to be analyzed in the Environmental Assessment (EA) and in identifying other information needs to support the environmental analysis.

NNMREC coordinated with the Collaborative Workgroup (CWG) that was established as part of the permitting process for PMEC-SETS to assess site characterization information needs and establish consensus on study plans to obtain that information. In addition, the Ecological Workgroup (EWG) considered a wide range of resources and site characteristics (receptors) in the context of Project structures and activities (stressors) to identity potential interactions. The group then reviewed potential interactions to determine where existing information could and should be augmented by site characterization studies. For potentially affected resources that are well-characterized by existing information and data, NNMREC coordinated with the CWG to collect information sources that could be used to inform the environmental. Where significant gaps were identified in the existing information, the group reviewed and refined the site characterization study plans developed as part of this task. The primary purpose of these site characterization studies was to obtain additional information about potentially affected resources in order to support the environmental analysis documentation that will accompany the FERC Draft and Final License Applications. Additionally, these study results, along with existing information and data, will help inform final Project design, as well as the development of monitoring plans, adaptive management, Best Management Practices (BMPs), and other Protection, Mitigation and Enhancement (PM&Es) measures to minimize and avoid potential effects.

Some of the site characterization and baseline data needs identified in the SOPO were later deemed through the permitting process not to be necessary. Additional studies were also identified through this process and through the final site identification process. EMF was identified in the SOPO as a site characterization need. Discussions with the CWG concluded that baseline EMF surveys were not necessary as post-installation monitoring would address potential EMF effects.

Building on the work described in Tasks 5.1 and 17.1, with the siting of the PMEC-SETS, in 2013 Henkel expanded the box core and CTD sampling to PMEC-SETS as well as initiated a study focused on Dungeness crabs around PMEC-SETS (Task 21.2.1); these benthic studies continued through 2015 to provide the two years of site characterization for PMEC-SETS. Starting in 2013, marine mammal and bird observers were present on nearly every single benthic survey cruise to NETS and SETS. Observers also frequently were onboard bi-weekly NOAA-sponsored cruises along the Newport Hydrographic Line. These survey efforts result in Suryan's team characterizing habitat utilization of various seabird species of concern, particularly in relation to PMEC-NETS and SETS (another key parameter for Task 21.2.1).

In 2014, following on the acoustic work at PMEC-NETS, Haxel deployed drifting passive hydrophones to provide "snapshot" data of acoustic conditions at PMEC-SETS. In 2015, a seafloor-mounted passive hydrophone was deployed for three months to provide a longer time series of acoustic conditions at PMEC-SETS.

To characterize marine mammals in the site, in 2015 DMONs were deployed at a station near PMEC-SETS and an inshore station; harbor porpoise vocalizations were detected >90% of the time on each hydrophone but differences in the types of vocalizations, indicating different behaviors, were detected between the two locations. These observations again provide important baseline data to be used to investigate potential effects of future facilities.

TRIAXYS data for two deployment months (November 9th 2014 to January 23rd 2015) is shown in Figure 37 as a percentage occurrence matrix. The most common conditions are wave periods of approximately 10 seconds and wave heights of approximately 2 meters. Figure 38 shows the time-series of significant wave heights (averaged over 20 minute intervals) for November 9th 2014 to January 23rd 2015. In Figure 38, several large peaks are evident, which correlate to stormier weather.

Height (m) \ Period (s)	5.1	6.2	7.3	8.5	9.6	10.7	11.8	13.0	14.1	15.2
0.9	0.8	3.1	3.6	2.9	2.1	0.6	0.0	0.0	0.0	0.0
1.5	0.1	1.5	2.7	4.6	4.6	4.6	0.8	0.1	0.0	0.0
2.1	0.0	0.1	0.8	3.4	5.5	5.2	2.9	0.2	0.1	0.0
2.7	0.0	0.0	1.4	2.3	4.2	4.7	3.6	0.5	0.4	0.2
3.2	0.0	0.0	1.2	2.3	3.9	4.8	2.9	0.7	0.2	0.0
3.8	0.0	0.0	0.0	0.7	1.8	2.6	1.6	0.6	0.2	0.1
4.4	0.0	0.0	0.0	0.3	0.8	2.1	0.6	0.4	0.1	0.1
5.0	0.0	0.0	0.0	0.1	0.4	1.1	0.9	0.2	0.2	0.1
5.6	0.0	0.0	0.0	0.0	0.3	0.1	0.4	0.2	0.0	0.1
6.1	0.0	0.0	0.0	0.0	0.1	0.4	0.1	0.1	0.0	0.0

Figure 37: Occurrence Matrix for November 9th 2014 to January 23rd 2015 at PMEC-SETS. Matrix entries are percentage of time.

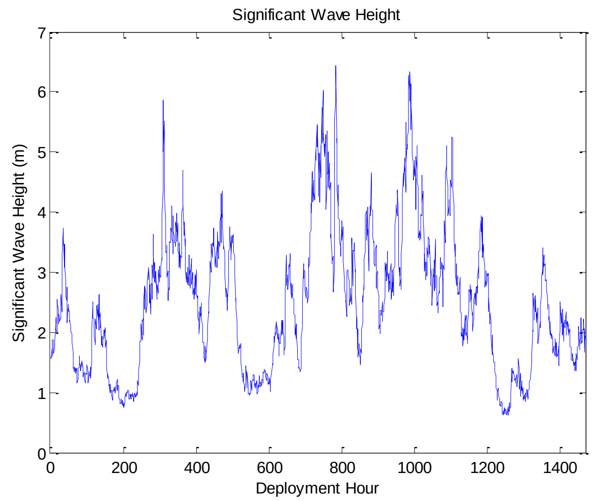

Figure 38: Significant Wave Heights for November 9th 2014 to January 23rd 2015at PMEC-SETS.

This work was prepared for publication and presentation at the Marine Energy Technology Symposium (METS) 2015 in Washington DC.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

The slower-than-expected progress with the development of PMEC-SETS, and the intensive permitting process has meant that some of the site characterization activities identified in the SOPO were conducted under this award but were reported out under award number DE-EE-0006518. Table 1 below summarizes the status of the site characterization components.

Table 1: Status of site characterization components.

Site Characterization Components	Comment	Status	Reporting
Seabirds	Added as part of permitting process	Completed under this award	Reported out under award number DE-EE-0006518
Acoustics	From SOPO	Completed under this award	Reported out under award number DE-EE-0006518
Marine Mammals	Added as part of permitting process	Completed under this award	Reported out under award number DE-EE-0006518
Benthic Habitat	From SOPO	Completed under this award	Reported out under award number DE-EE-0006518
Wave & Current	From SOPO	Completed under this award	See Task 16.1 section of this report.
Marine Survey	From SOPO	Completed under this award	Reported out under award number DE-EE-0006518
Vessel Traffic	Removed as part of permitting process. Not deemed an issue as data exist.	Study not undertaken but existing vessel AIS data mapped.	-
EMF	Postponed as part of permitting process.	Post-installation monitoring is planned.	-

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

Extensive site characterization efforts have been conducted in and around the PMEC-SETS project location. While the SOPO identified a number of likely site characterization requirements, these were refined as agencies and stakeholders identified the critical issues and data gaps. While the final site characterization components differed slightly from the SOPO, the accomplishments under this task have satisfied the needs of the agencies and stakeholders involved in the permitting process.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and related references for this research objective are described in detail in Appendix I.

PERMITTING: UTILITY CONNECTION (TASK 21.3)

ORIGINAL HYPOTHESES OR SCOPE

This effort will be conducted in collaboration with the Site Selection Process. In particular, a detailed strategy and timeline for the planning will be developed including study and interconnection for the primary sites under consideration. For each site under consideration, the strategy will include: 1) identifying required utilities (local PUD, BPA, and/or PacifiCorp); 2) determining most cost-effective and system efficient method of interconnection; 3) creating detailed review of the studies and process required to support interconnection; 4) creating detailed list of the system additions or upgrades required (e.g., additional lines, transformers, substations); 5) a summary of the cost and time required for additions or upgrades; and 6) identifying any interconnection concerns. Once a site is selected, interconnection process with the appropriate utility and/or group of utility entities will begin.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

NNMREC has: 1) identified all the relevant utilities; 2) determined a cost-effective and efficient approach to the interconnection process; and 3) created a detailed review of the studies and processes required to the support the interconnection process. The general approach included researching applicable information and engaging in individual meetings with relevant parties.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

It was determined the following tasks of: 1) creating detailed list of the system additions or upgrades required (e.g., additional lines, transformers, substations); 2) a summary of the cost and time required for additions or upgrades; and 3) identifying any interconnection concerns were unable to complete in final detail until the final site for interconnect is determined, and essentially is the responsibility of Bonneville Power Administration in coordination with NNMREC.

At the time of original scoping, it was unknown that NNMREC would need to rely on BPA to complete the above work. NNMREC has provided all the required information to BPA to complete the above tasks. It is anticipated final details of these tasks will be complete in 2016.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The primary differences in accomplishments from the original objectives relates to timing. During original scope, it was unknown that NNMREC would need to rely on BPA to complete the above work. NNMREC is waiting for BPA to complete the necessary work regarding: 1) creating detailed list of the system additions or upgrades required (e.g., additional lines, transformers, substations); 2) a summary of the cost and time required for additions or upgrades; and 3) identifying any interconnection concerns.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables for this research objective are described in detail in Appendix I.

CRITICAL INFRASTRUCTURE: MONITORING INSTRUMENTATION (TASK 22.1)

ORIGINAL HYPOTHESES OR SCOPE

This task will include designing, building, and demonstrating a low-cost system for recovering and redeploying an instrumentation suite connected to fiber optic communications and medium voltage power. The proposed approach is based around a "plug and socket" architecture, whereby the power and data cable for monitoring instrumentation is terminated at a fixed "socket", likely in close proximity to the device under test. Power and data connectivity to shore is via a single wet-mate connector, rather than individual wet-mate connectors for each instrument.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

After considering a number of alternatives, the project team modified an inspection-class ROV to perform a "docking" maneuver between an integrated instrumentation package (the Adaptable Monitoring Package, or AMP: Figure 39) and a "socket" containing a wet-mate power and fiber receptacle. This required hydrodynamic simulation and testing of the AMP and deployment ROV to minimize drag forces for available thrust. The project team successfully designed, built, and tested a prototype ROV system (constructed around a modified SeaEye Falcon) and AMP, successfully progressing from tank testing to open water deployment.

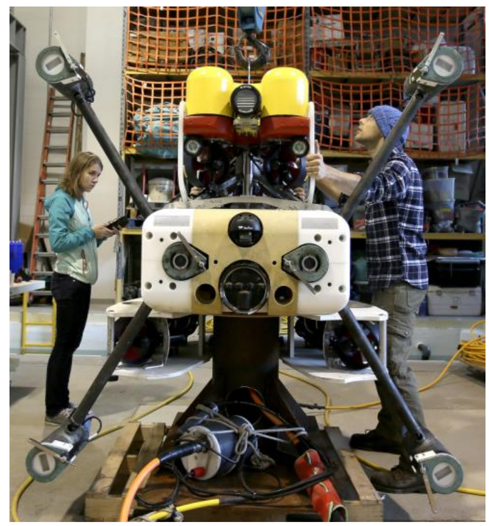

Figure 39: Pre-installation check-out of the Adaptable Monitoring Package (AMP) and "Millenium Falcon" ROV.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

Though the project scope was achieved, two aspects contributed to significant delays. The first was lead times for critical components. The wet-mate power and fiber connector, developed for oil and gas applications had a quoted lead time of 22 weeks, which was accurate. The linear actuators to engage the docking securement system and wet-mate connectors had much shorter quoted lead times, but were not delivered for almost 30 weeks. The second aspect that contributed to delays was the readiness of the linear actuators, which failed during system checkout on three occasions (for three different reasons) before the manufacturer was able to deliver a reliably functioning system. Despite these problems, the ROV system was used to deploy the AMP in Sequim Bay, WA for an endurance trial in January 2016, without the use of divers.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The accomplishments matched the original goals and objectives of the task, demonstrating the ability of an inspection-class ROV to deploy a relatively large integrated instrumentation package. This requires that the instrumentation package be optimized to minimize drag and that the centers of mass, pressure, and buoyancy achieve a balance of passive stability and maneuverability. Lower-cost options may be viable for some wave and current applications where a dedicated instrumentation system cable is available and precise redeployment is not required. However, the demonstrated system represents a significant cost improvement over deployment using large, specialized vessels or work-class ROVs and allows precise redeployment and sharing of a single export cable between a marine energy converter and a recoverable instrumentation package.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and related references for this research objective are described in detail in Appendix J.

CRITICAL INFRASTRUCTURE: GRID EMULATION (TASK 22.2)

ORIGINAL HYPOTHESES OR SCOPE

The intent of this task was for NNMREC to develop a design specification for a grid emulator for the testing of full-scale wave energy converters (WECs). This grid emulator would be installed at the onshore location of the PMEC South Energy Test Site (PMEC-SETS).

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

The NNMREC team worked to advance the grid emulator project through specification driven by the needs of the PMEC-SETS site, designed the emulator (see the grid emulator topology in Figure 40), and began lab hardware validation.

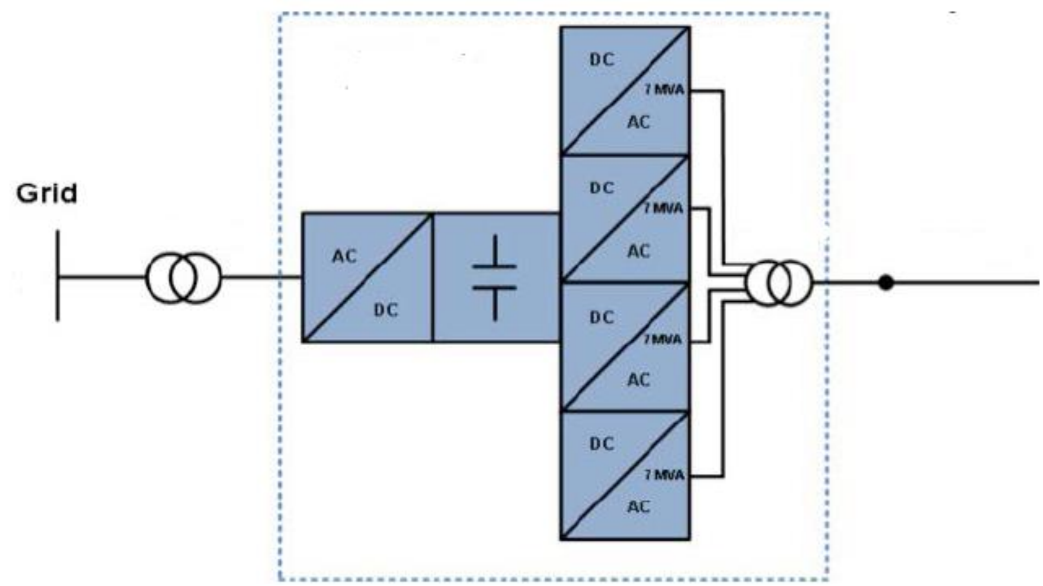

Figure 40: Grid emulator topology.

Existing grid emulation technologies were investigated, and models/simulations were developed to ensure proper device performance. For next-step hardware validation (based on future funding), the simulations would be integrated with hardware controllers as shown in the block diagram in Figure 41.

For the hardware validation, the researchers plan to use the ABB CGI (Controllable Grid Interface) controller in the WESRF lab. The NNMREC team worked in close collaboration with NREL, and would be using the same controller NREL uses for the CGI at their Wind Technology Center. The WESRF hardware validation would enable hardware-in-the-loop modeling to simulate operation with a wave energy converter under test.

Details of the in-lab hardware validation of the grid emulator include interfacing MATLAB Simulink models, developed with the grad students, with one of WESRF's dSPACE DS1103 PPC controller boards and the ABB controller using an EtherCAT interface.

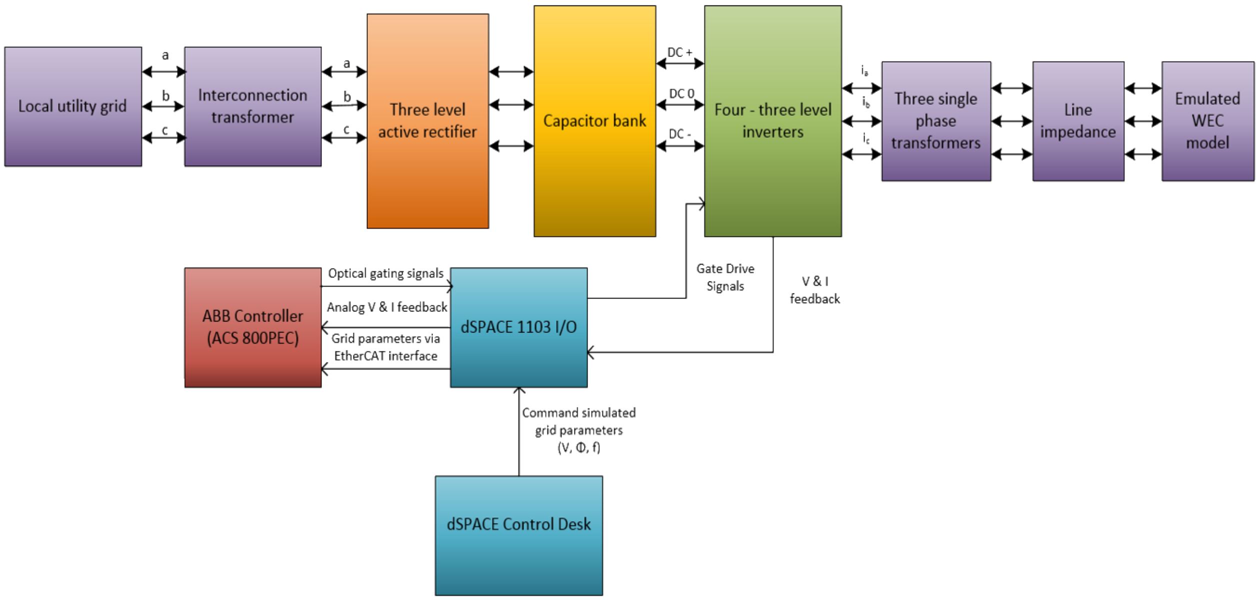

Figure 41: Planned grid emulator hardware-in-the-loop set-up in WESRF.

Technical details of this task can be found in Biligiri (2014), Biligiri et al. (2014b), Harpool (2015), von Jouanne et al. (2015).

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

For the planned grid emulator hardware verification work in WESRF, the availability of the ABB controller was delayed until March 31st, 2015 (date provided by ABB). It was therefore decided that the continuing work would be focused on advancing the grid emulator simulations.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

The original goals of this task, for NNMREC to develop a design specification for a grid emulator for the testing of full-scale WECs, was accomplished. As discussed above, it was planned that this would include hardware verification work in WESRF. However, since the availability of the ABB controller was delayed, it was decided that the continuing work would be focused on advancing the grid emulator simulations.

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Biligiri K., S. Harpool, A. von Jouanne, E. Amon, T. Brekken. (2014). Grid Emulator for Compliance Testing of Wave Energy Converters. 2nd *IEEE Conference on Technologies for Sustainability (SusTech)*. Portland, OR.

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von Jouanne A., T. Brekken, E. Cotilla-Sanchez, E. Amon, A. Yokochi. (2015). NNMREC PMEC-SETS Grid Emulator Array-to-Grid Transmission System and Wave Energy Resource Characterization. *3rd Marine Energy Technology Symposium* (METS). Washington DC.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix J.

CRITICAL INFRASTRUCTURE: ANCHORING AND MOORING (TASK 22.3)

ORIGINAL HYPOTHESES OR SCOPE

This research task was intended on the development of dynamic models for slack moored wave energy devices. The WEC and mooring system will be numerically modeled by NNMREC faculty to optimize the mooring system configuration in a way that minimizes costs. Additionally, a contract will be awarded to an ocean engineering company to perform an anchoring and mooring paper study with the goal of advancing the industry toward practical mooring systems. Such designs may be tested, at reduced-scale, in the wave tanks at OSU.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

Numerical models were developed for the study of dynamics of slack-moored WECs. These models were based on ORCAflex with large-body potential flow added mass and radiation damping characteristics determined by AQWA. A field test measuring the tension response of the Ocean Sentinel was conducted and a preliminary analysis of the resulting data was performed by Baker, a former MS student on the project (see Baker et al. (2014a), (2014b), and von Jouanne et al. (2014)). A more systematic analysis of the field data and comparison with numerical predictions is near completion and will be documented in a PhD thesis to be completed in 2016. Systematic design procedures for WEC devices including mooring system were developed (Bosma et al. (2012) and (2013)).

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

There were no problems encountered in this task. A field test on wave load on mooring lines was added. Field data collected are being analyzed. The analysis, when completed, will be of further benefit.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

There are no differences in the accomplishments and the original objectives of this task. The field data analysis will enhance the understanding on environmental loads on cable mooring lines.

REFERENCES CITED

Baker J., S.C. Yim, E. Amon, S. Moran, T. Lettenmaier and A. von Jouanne. (2014a). Mooring Analysis of a NOMAD Buoy through Experimental Testing and Numerical Simulation. *ASME 33rd International Conference on Ocean, Offshore and Arctic Engineering*. San Francisco, CA.

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DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix J.

CRITICAL INFRASTRUCTURE: COMPOSITE CABLES (TASK 22.4)

ORIGINAL HYPOTHESES OR SCOPE

One of the highest cost components of PMEC-SETS and any commercial development will be the power transmission cable. This task will investigate a modular composites design for mono-tethered mooring power transmission cable. The main design features for this advanced composites cored cables is a lightweight cable that has high strength and adaptable stiffness, superior fatigue resistance, and low maintenance. The design will look at coupling strong mooring capabilities and power transmission. The mono-cable will have advantages in deployment and reduce the WECs negative interactions with waves and tides. The tether can be passively tailored to the requirements of the specific WEC and location.

ACCOMPLISHMENTS, INCLUDING APPROACHES USED

A critical component of WEC systems and control scheme is the mooring. The mooring must safely hold the device on station without negatively affecting the device dynamics and energy extraction. Fatigue and abrasion loading is of considerable concern since WEC mooring systems are required to be long-term installations. To maximize the number of devices that can be installed in a given area, cost and operational footprint are also considered during the design process. Single point mooring systems are an attractive option for WEC developers due to relatively low costs and appeal to ocean users due to the use of fewer components and the smaller footprint.

Albertani's research effort has been focused on: 1) the mechanics and dynamics of a single point mooring system; 2) the development of a mooring cable design process; and 3) the investigation the effects of cable cross-sectional layout, material selection, and conductor design on cable properties. Mooring systems numerical simulations were run using the NNMREC Ocean Sentinel as WEC and OrcaFlex as software. The simulations generated cable loads in a design loop as discussed in (Miller (2015) and Miller and Albertani (2015)).

PMEC-NETS, off the coast of Newport, Oregon, was selected as location for this study, since it is the location where the Ocean Sentinel has been deployed in previous years and experimental data are available for validation. Final loads were determined using a center structural member (CSM) cable design with Vectran as the structural material. All other cable designs were designed based on these calculated loads. After all cables were designed, the CSM cable design for each material was modeled again in OrcaFlex. A simplified calculation of loads was performed using estimated wet weight of each cable design, and the estimated vertical acceleration of the water surface caused by waves.

Electrical requirements for the mooring cable were based on the Ocean Sentinel umbilical cable. The cable must include three main power conductors sized at 2 American Wire Gauge (AWG) or larger, one ground conductor sized at 4 AWG or higher, and 2 auxiliary power conductors sized at 12 AWG or larger. Current and voltage specifications for the main conductors are 1) 120 Amps at 440 VAC, and 2) 50 Amps at 230 VAC. For electrical component design allowable resistance was used in place of allowable voltage drop (V_{Drop}).

Materials selected for structural components were Vectran HS, Kevlar 49, Carbon in a vinyl ester matrix (referred to as CFRP for this study), and MP35N. These four materials were selected to gain an understanding of how synthetic fibers and CFRP composites compared with comparable metallic cables. Vectran HS yarn was used as the starting material for each design since it is a well known material and traditionally used in current mooring cables. Kevlar 49 yarn is also commonly used in mooring cables. CFRP was used to examine the feasibility of application in mooring applications and electro-mechanical cables. Vinyl ester was used as the matrix material due to excellent water resistance. MP35N was included because it is a metal alloy currently used in structural members of electro-mechanical cables, and can provide a benchmark to compare fiber and CFRP cables.

Center conductor core (CCC), and center strength member (CSM) styles combined were used to generate six different cable designs. The six cable designs, were selected to evaluate and compare the mechanical characteristics of cables with different cross sectional layouts and structural component orientation. Each cable design originally used Vectran fibers as the structural material. Once each design was completed it was adapted to use Kevlar 49 yarn, and in some cases pultruded CFRP rods, and MP35N rods. The purpose of using multiple materials for each design was to gain an understanding of how different materials will function in a cable assembly. All CCC cables began by sizing the electrical components, while all CSM cables began by sizing the structural component. Five designs contained an electrical component with 22, 8 AWG wires. Using the same electrical component for these five designs allows for a better understanding of how the structural components in each design compare. The sixth design's electrical component consisted of 3, 2 AWG, and 12, 14 AWG wires. Design six was used to determine the effect of the electrical component on cable characteristics.

Each structural component was designed to carry the entire expected load per DNV-OS-301. Design of the cable structural component began by determining the total allowable cable strain 0.1%. After the required axial stiffness was determined the best combination of number of strands, and strand helical angle were determined. Several iterations were required to find a suitable combination of strands and helical angles. When the number of strands and helical angle was determined, equations were used to determine the required strand stiffness. The axial stiffness of the untwisted yarn bundle was then used to determine the required cross sectional area of each untwisted strand, and the required number of filaments per strand. CSM cable designs using either CFRP or MP35N as the structural material were not able to use a braid as the structural member. Instead cables using either material in a CSM configuration used a fiber core wire rope. For CCC cable designs using Vectran and Kevlar fibers oriented in hollow braids, the braid size was estimated based on strand and cable core diameters. Braid thickness of each layer was estimated at twice the strand diameter due to strand cross over points along the braid.

Electrical conductors were helically wrapped about the cable center axis in each cable design to limit total tensional loads during use. There is a maximum helical angle for a given strand and core size that is allowable before no additional room is available in that layer, and no additional strands will fit. To verify that each conductor design was possible, the maximum coil angle of each layer was determined, and compared to the design helical angle. If the design helical angle was smaller, the design was possible. Following the initial design of both structural and electrical components, each cable was adjusted using equations to ensure torque balance while under load. Cable diameter, axial stiffness, bending stiffness, minimum bend radius, maximum load, and tensile fatigue life properties were estimated to analyze each cable design, and structural material.

Minimum bend radius, a critical feature for a practical cable, was analyzed for all designs. Allowable strain for conductors was one third of the lowest allowable strain for any structural material, so minimum bend radius was assumed dependent on the conductors. Assuming no slippage occurring between the cable core and any conductor CCC designs had lower minimum bend radii than CSM designs for all materials.

Dynamic simulations demonstrated that Vectran, CFRP, and MP35N show similar load amplitudes at low frequency, while Kevlar shows lower amplitude loads at low frequencies. As the frequency increases, Vectran, Kevlar, and CFRP start to exhibit similar loading amplitudes while MP35N begins to deviate from the other cables. Fatigue characteristics were also estimated for all six designs.

Cable design affected cable properties and cable fatigue life minimally. Changing the electrical component configuration, and using structural layers to balance tensile induced torque caused by the electrical components could lead to similar mechanical properties for CCC and CSM designs. CCC-CSM combination designs had similar performance characteristics to CCC and CSM cables, but cannot be modified as easily as CCC or CSM designs. CCC and CSM were found practical design options while CCC-CSM combinations were found impractical due to increased complexities in the cable and termination designs. Cables with synthetic fibers (Vectran and Kevlar) exhibited longer fatigue life and higher maximum cable loads when compared with CFRP and MP35N cables. Axial stiffness, minimum bend radius, and bending stiffness were not significantly affected by material choice. Component helical angle was the only design consideration which exhibited a significant impact on all mechanical properties of a cable. Marine device heave motion and mooring cable tension are not significantly affected by changes in cable structural materials or cable design. Materials selected will mainly affect service life and cost of the cable system.

PROBLEMS ENCOUNTERED AND DEPARTURE FROM PLANNED METHODOLOGY; ASSESSMENT OF IMPACT ON PROJECT RESULTS

No problems encountered or departure from planned methodology.

HOW ACCOMPLISHMENTS COMPARED WITH THE ORIGINAL GOALS AND OBJECTIVES OF THIS TASK

No differences in accomplishments as compared with the original goals of the project subtask.

REFERENCES CITED

Miller A. (2015). Fiber Reinforced Composite Power-Mooring Cables Design and Manufacturing applied to Wave Energy Converters. Master's thesis, Oregon State University.

Miller A., R. Albertani. (2015). Single-Point Power-Mooring Composite Cables for Wave Energy Converters. *Journal of Offshore Mechanics and Arctic Engineering*. doi: 10.1115/1.4030900.

DELIVERABLES FROM THIS RESEARCH OBJECTIVE

The deliverables and additional related references for this research objective are described in detail in Appendix J.

PRODUCTS DEVELOPED UNDER THIS AWARD

Lists of relevant products will be included under each subheading, with explanations when necessary

WEBSITES

To support the work under this project, OSU and UW developed NNMREC websites. They can be found at nnmrec.oregonstate.edu and depts.washington.edu/nnmrec, respectively.

COLLABORATIONS

NNMREC developed an extensive list of collaborators through this project; the following list includes collaborators that both directly contributed to the project:

- Aquatera
- AXYS Technologies
- BioSonics
- Ecology and Environment
- European Marine Energy Centre
- Fishermen Involved in Natural Energy
- GNV-DL
- HDR Engineering
- HT Harvey & Associates
- ICF International
- National Renewable Energy Laboratory
- Orcades Marine
- Oregon Wave Energy Trust
- Pacific Energy Ventures
- Pacific Northwest National Laboratory
- Port of Newport
- Port of Toledo
- SAIC
- Sapere Consulting
- Sandia National Laboratory
- Sound & Sea Technology
- Sea Mammal Research Unit
- 3U Technologies

INVENTIONS, PATENT DISCLOSURES, LICENSING AGREEMENTS

"A Heave-plate mooring for wave energy conversion via changing loads", J. Thomson, J. Talbert, A. deklerk; provisional patent application number 61/664,444; docket number OSC-P016P, 2013.

Dates represent the year of degree; no date indicates the degree is still in process; students receiving MS degrees and continuing for PhD are listed twice, once under each degree

Student	Thesis/Dissertation Title	Current Employment
Ph.D.		
Amon, Ean **Electrical Engineering, OSU**	Development of Control Topologies for Ocean Wave Energy Devices Utilizing a Novel Power Analysis and Data Acquisition System (2010)	Columbia Power Technologies
Barber, Ramona **Civil Engineering, UW**	Passive Pitch Control in Marine Hydrokinetic Turbine Blades	
Boren, Blake **Mechanical Engineering, OSU**	Vertical Axis Pendulum Wave Energy Converters : Investigating Control Strategies and the Deployment of a Scaled Generic Prototype (2015)	Wavepower
Bosma, Bret **Electrical Engineering, OSU**	A Design Guide for Wave Energy Developers (2013)	Staff Engineer, OSU
Bunn, Malachi **Chemical Engineering, OSU**	Development and Validation of an Electrochemical Reaction/Diffusion/Convection Model for the Electrochemical Biofouling Protection of Surfaces (2014)	Epic
Brown, Adam **Mechanical Engineering, OSU**	On the Effects of Breaking Waves on Deep Water Wave Energy Converters (2014)	Postdoctoral Researcher, UW
Cavagnaro, Rob **Mechanical Engineering, UW**	Performance Evaluation, Emulation, and Control of Cross-Flow Hydrokinetic Turbines (2016)	Postdoctoral Researcher, UW
Challa, Ravi **Civil Engineering, OSU**	Hydrodynamic Contact/Impact Modeling and Application to Ocean Engineering Problems (2014)	Postdoctoral Researcher, OSU
Davis, Andrew **Mechanical Engineering, OSU**	Dynamic Modeling and Control of WEC Mooring Systems	
Honegger, David **Civil Engineering, OSU**	Partially supported by NNMREC; moved onto a different research project	Postdoctoral Scholar, OSU
Javaherchi, Teymour **Mechanical Engineering, UW**	Numerical investigation of Marine Hydrokinetic Turbines: methodology development for single turbine and small array simulation, and application to flume and full-scale reference models (2014)	Lecturer, UW
Joslin, James **Mechanical Engineering, UW**	Advancing Marine Renewable Energy Monitoring Capabilities (2015)	Staff, UW
Lettenmaier, Terry **Electrical Engineering, OSU**	Testing of Wave Energy Converters using the Ocean Sentinel Instrumentation Buoy (2013)	Consultant
Lewis, Tim **Electrical Engineering, OSU**	Design and Control of an Autonomous Two-Body Wave Energy Converter for maximum Power Absorption (2013)	Orbital ATK

Lou, Junhui **Civil Engineering, OSU**	Real-Time Estimation and Prediction of Wave Excitation Forces for Wave Energy Control Applications	
Newborn, David **Civil Engineering, OSU**	Experimental observations and numerical simulations of wave impact forces	Naval Surface Warfare Center, Carderock Wave Testing Facility
Nichol, Tyler **Mechanical Engineering, UW**	Dynamic Modeling of Slack Moored Tidal Turbines	
Nimmala, Seshu **Civil Engineering, OSU**	An Efficient High-Performance Computing Based Three-Dimensional Numerical Wave Basin Model for the Design of Fluid-Structure Interaction Experiments	Lam Research Corporation
Polagye, Brian **Mechanical Engineering, UW**	Hydrodynamic Effects if Kinetic Power Extraction by In-Stream Turbines (2009)	Faculty, UW
Simmons, Asher **Electrical Engineering, OSU**	Methods for estimating mechanical power available for conversion from small-scale wave energy experimental data	
Stillinger, Chad **Electrical Engineering, OSU**	On the Study of WEC Prototype Advancement with Consideration of Real-Time Life Extending Control (2011)	Faculty, George Fox University
Thyng, Kristen **Mechanical Engineering, UW**	Numerical Simulation of Admiralty Inlet, WA, with Tidal Hydrokinetic Turbine Siting Application	Faculty, Texas A&M University
M.S.		
Adamski, Samantha **Mechanical Engineering, UW**	Numerical Modeling of the Effects of a Free Surface on the Operating Characteristics of Marine Hydrokinetic Turbines (2013)	Newport Engineering (US Navy) Bremerton, WA
Barber, Ramona **Civil Engineering, UW**	Passive Pitch Control in Marine Hydrokinetic Turbine Blades (2015)	PhD Student, UW
Biligiri, Kaushal **Electrical Engineering, OSU**	Grid Emulator Project (2013)	Schneider Electric
Boren, Blake **Mechanical Engineering, OSU**	Modeling and Control of Horizontal Pendulum Wave Energy Converters (2013)	Wavepower
Black, Colleen **Civil Engineering, OSU**	Wave Scattering in the Near-field of a WEC-array via Stereo Video Measurements (2014)	Moffatt & Nichol
Casey, Sean **Mechanical Engineering, OSU**	Comparison of passive and active controlled hydraulic power take off systems for wave energy conversion (2013)	Energy Storage Systems
Challa, Ravi **MS Civil Engineering, OSU**	Contact and Impact Dynamic Modeling Capabilities of LS-DYNA for Fluid-Structure Interaction Problems (2010)	Lam Research Corporation
Collins, Erin **Mechanical Engineering, OSU**	Sustainability Analysis and Design for a Point Observer Mooring System (2014)	moovel Group
Delaney, Matthew **Chemical Engineering, OSU**	Study of Graphite-Polyurethane Composite Thin Film Electrodes for Their Use in Electrochemical Antifouling Systems (2011)	Sandia National Laboratory
Epler, Jeff **Mechanical Engineering, UW**	Tidal Resource Characterization from Acoustic Doppler Current Profilers (2010)	Markley Machinery

Fry, Brady **Electrical Engineering, OSU**	Systems Design and Integration of EM Sensor Platforms	
Garcia-Castano, Manuel **Civil Engineering, OSU**	Optimization of power extraction of arrays of Wave Energy Converters (WECs) and their influence on the wave climate (2015)	Moffatt and Nichol
Gooch, Sam **Mechanical Engineering, UW**	Tidal Site Characterization (2009)	Apple
Goodwin, Briana **Marine Resource Management, OSU**	Evaluating Community Engagement in Wave Energy Siting off the Oregon Coast	AquaFish Innovation Lab
Haegele, Chase **Mechanical Engineering, UW**	Wake Characterization of a Cross-Flow Turbine (2014)	Adecco Group
Harpool, Scott **Electrical Engineering, OSU**	Aggregated Reserve Requirements of Geographically Diverse Renewable Portfolios in the Pacific Northwest	PhD Student, OSU
Henshaw, Nathan **Electrical Engineering, OSU**	A Force Control Algorithm for a Wave Energy Linear Test Bed	Employer unknown
Holdman, Amanda **Fisheries and Wildlife, OSU**	Spatiotemporal patterns of porpoise presence at the Pacific Marine Energy Center off Newport, Oregon	
Hovland, Justin **Mechanical Engineering, OSU**	Predicting Deep Water Breaking Wave Severity (2010)	Energy 350, Inc.
Hunyh, Kristina **Oceanography, UW**	Simulation of Estuarine Dynamics (2013)	Zillow
Kassem, Sarah **Ocean Engineering, OSU**	Wave Modeling at the Mouth of the Columbia River (2010)	H. R. Wallingford, Oxford, UK
Lenee-Bluhm, Pukha **Mechanical Engineering, OSU**	The Wave Energy Resource of the US Pacific Northwest (2010)	Columbia Power Technologies
Ling, Bradley **Mechanical Engineering, OSU**	Real-Time Estimation and Prediction of Wave Excitation Forces for Wave Energy Control Applications (2015)	Northwest Energy Innovations
McArthur, Shaun **Electrical Engineering, OSU**	Residential Load Simulation and Applied Load Management Strategies (2011)	Employer unknown
McNatt, Cameron **Ocean Engineering, OSU**	Wave Field Patterns Generated by Wave Energy Converters (2012)	Founder of Mocean Energy
Meicke, Steven **Mechanical Engineering, OSU**	Hydroelastic Modeling of a Wave Energy Converter using the Arbitrary Lagrangian-Eulerian Finite Element Method in LS-DYNA (2012)	HDR Engineering
Mendoza, Maritza **Marine Resource Management, OSU**	Evaluation of environmental effects of anchor deployment	
Miller, Andrew **Mechanical Engineering, OSU**	Fiber Reinforced Composite Power-Mooring Cables Design and Manufacturing applied to Wave Energy Converters (2015)	Columbia Helicopters

Moon, Ruby **Public Policy, OSU**	IDA Framework to Examine the Relationship Between Regulating Enforcers and the Commercial Trawl Fishery of Newport, Oregon (2012)	Community Health Director at Confederated Tribes of Siletz Indians
Murphy, Paul **Mechanical Engineering, UW**	Estimation of Acoustic Particle Motion and Source Bearing Using a Drifting Hydrophone Array near a River Current Turbine to Assess Disturbances to Fish (2015)	Staff, University of Washington
Niblick, Adam **Mechanical Engineering, UW**	Experimental and Analytical Study of Helical Cross-Flow Turbines for a Tidal Micropower Generation System (2012)	Creare, Inc.
Nichol, Tyler **Mechanical Engineering, UW**	Dynamic Modeling of Slack Moored Tidal Turbines (2013)	PhD student, UW
O'Dea, Annika **Civil Engineering, OSU**	Nearshore Effects of WEC-arrays at Oregon Coastal Sites (2014)	PhD student, OSU
Oskamp, Jeffrey **Ocean Engineering, OSU**	Toward Wave Energy in Oregon: Predicting Wave Conditions and Extracted Power (2011)	Moffatt & Nichol
Porquez, Jessica **Marine Resource Management, OSU**	Spatiotemporal patterns of porpoise presence at the Pacific Marine Energy Center off Newport, Oregon	
Porter, Aaron **Civil Engineering, OSU**	Laboratory Observations and Numerical Modeling of the Effects of an Array of Wave Energy Converters (2012)	Coast & Harbor Engineering
Ruehl, Kelley **Mechanical Engineering, OSU**	Time-Domain Modeling of Heaving Point Absorber Wave Energy Converters, Including Power Take-Off and Mooring (2011)	Sandia National Laboratories
Simmons, Asher **Electrical Engineering, OSU**	A Frequency-Domain Approach to Simulating Wave Energy Converter Hydrodynamics (2013)	PhD student, OSU
Stelzenmuller, Nick **Mechanical Engineering, UW**	Marine Hydrokinetic Turbine Array Performance and Wake Characteristics, (2013)	PhD student, University of Grenoble
Stelzenmuller, Nick **Mechanical Engineering, UW**	Experimental Flume Testing of an Array of Scale MHK DOE Reference Model 1 Turbines (2013)	Employer unknown
York, Charles **Electrical Engineering, OSU**	Modeling and Experimental Verification of Electric and Magnetic Fields Generated by Undersea Power Transmission cables (2010)	Bonneville Power Administration
B.S.		
Beba, Tricia **UW**	An Investigation of Turbine Depth on Device Performance in a Sheared Flow (2011)	Formerly of DNV KEMA Inc. (a wind energy company)
Freund, Elizabeth **Chemical Engineering, OSU**	Evaluation of Electrochemical Biofouling Prevention of Transparent Conductive Oxide Films in Seawater (2013)	PhD Student, Case Western Reserve University
Gedney, Marisa **Oceanography, UW**	Tidal energy extraction in an idealized ocean-fjord tidal model with astronomical forcing (2013)	
Jordan Pommerenck **Physics, OSU**	Characterization of super-low frequency electromagnetic fields produced by an undersea transmission cable in a homogeneous fluid	

MODELS DEVELOPED UNDER THIS AWARD

SWAN MODEL, DELIVERABLES 1.1, 2.1.2, 8.1.3, 8.1.4, 11.4

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

SWAN: Simulating Waves Nearshore, a third-generation wave model for coastal regions (http://www.swan.tudelft.nl/). SWAN can be used freely under the terms of the GNU General Public License. SWAN accounts for the following physics:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth.
- Wave generation by wind.
- Three- and four-wave interactions.
- Whitecapping, bottom friction and depth-induced breaking.
- Dissipation due to aquatic vegetation, turbulent flow and viscous fluid mud.
- Wave-induced set-up.
- Propagation from laboratory up to global scales.
- Transmission through and reflection (specular and diffuse) against obstacles.
- Diffraction.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

For use in this project a spectral wave transformation model capable of simulating waves in domains of order 10km x 10km with resolutions of order 10m and with runtimes of order 10-100x compared to real time was necessary.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

A hindcast simulation of the Newport domain was performed to validate the model setup. This was documented in the following publications:

O'Dea A. (2014) On the nearshore impact of wave energy converter arrays. Master's thesis, Oregon State University.

O'Dea A., M.C. Haller, H.T. Özkan-Haller. (2015). The impact of wave energy converter arrays on wave-induced forcing in the surf zone. Submitted to *Renewable Energy*.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

Linear water wave theory including wave-current interaction with additional parameterizations to account for some nonlinear aspects and wave dissipation.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

SWAN is built upon a finite difference solution of the wave-action balance equation.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

The original formulation of the SWAN model was documented in the following publication:

Booij N., R.C. Ris, L.H. Holthuijsen, L.H. (1999). A third-generation wave model for coastal regions 1. Model description and validation. J. Geophys. Res., 104 (C4), 7649-7666.

This paper has been cited over 1100 times (Web of Science). Hence, the strengths and weaknesses of the model are well documented in the literature. The SWAN model is presently considered the state-of-the-art in mesoscale, high-resolution coastal wave transformation studies.

HARDWARE REQUIREMENTS

Source code and implementation information are well described on the SWAN website here: http://swanmodel.sourceforge.net/download/download.htm

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

SWAN team. (2006a). SWAN Technical Documentation. Delft University of Technology.

SWAN team. (2006b). SWAN User Manual. Delft University of Technology.

http://swanmodel.sourceforge.net/online_doc/swanuse/swanuse.html

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

The WAVEWATCH III v3.14 (WW3; Tolman 2002b) is a third-generation phase-averaged wave model developed by NOAA's National Center for Environmental Prediction. It that solves the spectral wave action balance equation over a regular (latitude, longitude) grid. WAVEWATCH III accounts for the following physics:

- Wave growth and decay due to the actions of wind, nonlinear resonant interactions, dissipation (`whitecapping'), bottom friction, surf-breaking (i.e., depth-induced breaking) and scattering due to wave-bottom interactions.
- Wave propagation is modeled using linear water wave theory. Any nonlinear effects are included as source/sink terms.

Several options exist for source term packages. We have utilized the default ST2 physics package.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

The implementation is built taking advantage of WAVEWATCH III v3.14's mosaic nesting capabilities. Having multiple nested grids focuses the computational resources where they are needed. Waves in intermediate to shallow waters are affected by the bathymetry; therefore, higher resolution. The global grid provides near-global coverage at 1.258° × 1.008° resolution, in the latitudinal and longitudinal directions, respectively. It covers a region from 77°S to 77°N. The Eastern North Pacific covers a region from 5° to 60.25°N and from 170° to

77.5°W with 15-arc-minute resolution. To account for local bathymetric features on the

Oregon continental shelf outer grid covers a region from 41.45° to 47.50°N and from 127° to 123.75°W with 3-arc-minute resolution. The outer grid interacts with three highly resolved shelf grids that have resolutions of 30 arc seconds. These grid points are spaced 927m apart in the alongshore direction, resulting in 510 cells along the Oregon coast. In the across-shelf direction the grid spacing varies from 694 to 627 m, depending on the latitude.

Starting from the estimated conditions for TAU 00, we then perform a wave forecast with a TAU +84-h horizon. For the wave forecasting model, wind forecasts are downloaded from the GFS ftp server at 1610 UTC, and the forecasting model is initiated immediately. Currently, the model runs on 44 threads on two UNIX servers that have two six-core Intel Xeon CPUs clocking at 2.7GHz. The forecasts are completed around 0100 UTC of the next day, and forecasts for nearly 3 days (~71 h) become available at that time.

Note that these forecasts are being transitioned to the national Weather Service Portland and Medford Offices.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Extensive model performance testing was carried out an is documented in

García-Medina G., H. T. Özkan-Haller, P. Ruggiero, J. Oskamp. (2013): An inner-shelf Wave Forecasting System for the US Pacific Northwest. *Weather and Forecasting*. 28, 681-703.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

Linear water wave theory including wave-current interaction with additional parameterizations to account for wave growth and dissipation as well as nonlinear aspects and wave dissipation.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

WAVEWATCH III uses finite difference methods over a regular grid to solve the time-dependent wave action balance equation in the presence of various source and sink functions.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

The WAVEWATCH III formulation is documented in

Tolman, 2002: Validation of WAVEWATCH III version 1.15 for a global domain. NOAA/NWS/NCEP/OMB Rep. 213, 33 pp.

Tolman, 2006: Development of a multi-grid version of WAVEWATCH III. NOAA/NWS/NCEP/MMAB Tech. Rep. 256, 88 pp.

Tolman, 2008: A mosaic approach to wind wave modeling. Ocean Modelling, 25, 35–47.

HARDWARE REQUIREMENTS

Source code and implementation information are well described on the WAVEWATCH III website http://polar.ncep.noaa.gov/waves/wavewatch/wavewatch.shtml

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

WAVEWATCH is well documented. Materials can be found online at

http://polar.ncep.noaa.gov/waves/wavewatch/wavewatch.shtml

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

WAMIT is a state-of-the-art commercial boundary element solver that predicts the interaction of linear hydrodynamic forces and wave fields due to planar waves incident on ocean structures. It solves the standard linear wave-body boundary value problem in the frequency domain. The assumptions underlying the model are that 1) the fluid is incompressible, inviscid, and the flow is irrotational, so the velocity can be expressed as the gradient of a scalar velocity potential; 2) the wave height is small compared to the wavelength and water depth; and 3) the amplitudes of body motions are small compared to the size of the body. The latter two assumptions enable the use of linear wave theory. To find the solution to the boundary-value problem, WAMIT uses the boundary-element method, in which all body surfaces are represented as source or dipole functions that satisfy the governing equation (Laplace's equation for the velocity potential) and the free surface condition; the magnitudes of the dipole functions satisfy the no-penetration condition on all wetted surfaces.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

For use in this project, we have modeled the behavior of point-absorber WECs represented as simplistic cylindrical geometries allowed to move in heave or surge. Although a cylinder is a very rough approximation of a point-absorber WEC, the behavior of the cylinder can be controlled to closely mimic a realistic WEC. First, the dimensions of the cylinder are chosen to match the approximate size of the physical model. Second, the single degree-of-freedom mode of motion was chosen to correspond to the physical model WEC under consideration. Finally, a PTO damping for the computational model WEC was chosen so that the peak absorbed power was of the same approximate magnitude and occurred at approximately the same frequency as the physical model.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Model results are verified with laboratory observations of an array of WECs in

Özkan-Haller, H.T., M.C. Haller, J.C. McNatt, A. Porter, P. Lenee-Bluhm. Analyses of wave scattering and absorption produced by WEC-arrays: Physical and numerical experiments and an assessment of nearshore impacts. *In review*.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

Linear and second-order potential theory is used to analyze the behavior of floating or submerged bodies in the presence of ocean waves. Separate solutions are carried out simultaneously for the diffraction problem and the radiation problems for each of the prescribed modes of motion of the bodies. These solutions are then used to obtain the relevant hydrodynamic parameters including added-mass and damping coefficients, exciting forces, response-amplitude operators (RAOs), the pressure and fluid velocity, and the mean drift forces and moments. The second-order module provides complete second-order nonlinear quantities in addition.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

The boundary integral equation method is used to solve for the velocity potential using Laplace's equation for the velocity potential as a governing equation.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

WAMIT is extensively documented in the peer-reviewed literature. A notable publication is

Lee, C.H., Newman, J.N. (2004). Computation of wave effects using the panel method. In *Numerical models in fluid-structure interaction.* Preprint, Editor S. Chakrabarti, WIT Press, Southampton, 2004. (Copyrighted by WIT Press.)

For a list of related publications, see http://www.wamit.com/publications.htm.

HARDWARE REQUIREMENTS

Hardware requirements for the latest version can be found at http://www.wamit.com/version7.0.htm.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

WAMIT documentation is online at http://www.wamit.com/index.htm.

MODEL DESCRIPTION FOR DELIVERABLE 2.1.4

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

Predictive control model based off of simple linear hydrodynamics. Intended use is for short-horizon predictive modeling for estimation and control.

Assumptions:

Linear and frequency invariant added mass, hydrostatic stiffness, and radiation damping.

Motion-independent excitation force.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

Model sample time should be set sufficiently small to capture desired highest-frequency wave dynamics.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Model is based on well-known Morison hydrodynamics.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

If wave excitation and power-take-off excitation forces are known, wave energy converter motion is deterministic. The model is used to calculate the sequence of power-take-off excitation forces required to achieve a desired motion, usually optimal power capture.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

The model is based on Morison hydrodynamics and Model Predictive Control theory.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

The formulation was peer reviewed in

Brekken T.K.A. (2011). On model predictive control for a point absorber wave energy converter. *PowerTech*. Trondheim, Norway. pp. 1–8.

Strengths are simplicity and speed. Weaknesses are accuracy, especially for large motions and steep waves.

HARDWARE REQUIREMENTS

None.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

Brekken T.K.A. (2011). On model predictive control for a point absorber wave energy converter. *PowerTech*. Trondheim, Norway. pp. 1–8.

An additional paper on the control model used for Model Predictive Control of the Centipod device is under development.

ACTUATOR DISK MODEL RELATED TO DELIVERABLES 2.2.1, 8.2.1, 8.2.3

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

The Actuator Disk Model was employed in the study of turbine wakes and flow redirection. The actuator disk model describes the momentum deficit created by a disk representing the turbine rotor. It was used under Fluent Ansys v14 with the following assumptions:

The momentum deficit caused by the rotor disk has two terms proportional to the velocity (viscous) and to the velocity squared (inertial). The coefficients for these terms can be related to the turbine efficiency and drag coefficient.

The induction factor and thrust or drag coefficient are known for one operating condition isolated from all interference with the ambient (bottom floor, free surface, turbine support structure, incoming velocity shear, etc.) and these values are used to find the parameters in the numerical model that are input into the simulations.

The Actuator Disk model was used to represent turbines in preliminary studies of turbine wakes, as well as in very large arrays for flow redirection in domains with realistic bathymetry representing Puget Sound.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

The Actuator Disk Model was used in simulations of turbine and array domains that required low sensitivity to turbine parameters and allow for rapid turnover of results. Typical simulations used computational grids with <1 Million cells and provided results within a few hours of computer clock time. Accuracy was expected to match efficiency within 5% of experimental or higher resolution model results, with wake velocity profile matching results within 10% at locations 3 rotor diameters behind the turbine.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Numerical Simulations of single turbine and small arrays were conducted to validate this model. Performance was documented in the following publications:

Javaherchi T., A. Aliseda, S. Antheaume, J. Seydel, B. Polagye. (2009). Study of the turbulent wake behind a tidal turbine through different numerical models. *APS 62nd DFD Meeting*. Minneapolis, MN. USA.

Javaherchi T., A. Aliseda. (2010). Numerical Modeling of Hydrokinetic Turbines and their Environmental Effects. *APS 63rd DFD Meeting*. Long Beach, CA.

Javaherchi, T. (2010). Numerical Modeling of Tidal Turbines: Methodology Development and Potential Physical Environmental Effects. Master's Thesis. University of Washington

Javaherchi, T., N. Stelzenmuller, A. Aliseda. (2014) Experimental and Numerical Analysis of a Scale-Model Horizontal Axis Hydrokinetic Turbine. *2nd Marine Energy Technology Symposium.* Seattle, WA.

Stelzenmuller, N., A. Aliseda, A. (2012). An experimental investigation into the effect of Marine Hydrokinetic (MHK) turbine array spacing on turbine efficiency and turbine wake characteristics. *APS 65th DFD Meeting*. San Diego, CA.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

Actuator Disk Model uses the Linear Momentum Theory and assumes the turbine rotor behaves as a porous disk that produces a drop in linear momentum and energy in the flow as it crosses the disk.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

The Actuator Disk Model uses the classical formulation in W.J.M. Rankine (1865), Alfred George Greenhill (1888) and R.E. Froude (1889).

Froude R.E. (1889). On the part played in propulsion by difference of fluid pressure. *Trans Inst Naval Arch*, 30:390–405.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

This formulation has been used for over a century in the naval and aerospace fields, as well as in chemical mixing, aeration, etc. It has resulted in thousands of peer-reviewed publications that reference and expand over the original 19th century formulation.

HARDWARE REQUIREMENTS

ADM can be run on any desktop server with minimal RAM and CPU requirements. For the purposes of the simulations conducted in this project, different servers with 8-24 cores and 32-96 Gb of RAM were used. Fluent v14 was the computational platform of choice. More information about the requirements for Fluent v14 and the ADM implementation within it can be found in the users manual.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

ANSYS FLUENT 12.0, User's Guide, Chapter 7, Section 7.2.3, Porous Media Condition. URL http://www.fluentusers.com/fluent/doc/ori/v121/fluent/fluent12.1/help/html/ug/node256.htm.

BLADE ELEMENT MODEL RELATED TO DELIVERABLES 2.2.1, 8.2.1, 8.2.2, 8.2.3, 14.2.2

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

The Blade Element Model was employed in the study of turbine wakes, flow redirection, calibration by field and flume data, engineering rules for large arrays and empirical device spacing rules. The blade element model describes the forces that the turbine rotor exerts on the fluid passing through it. In the Fluent Ansys implementation used in this project, the rotor is divided into concentric rings and the force on a section of the blade at the radial position of the ring (the blade element) is calculated via tables of drag and lift coefficients for the shape of the blade section (NACA 4415 in this case). The local relative flow velocity between the fluid stream and the blade section are computed from the simulated flow field and this provides the angle of attack and Reynolds number on which the C_D and C_L depend, as well as the $\frac{1}{2} \rho v^2$ term that provides the magnitude of the forces. The model relies on the following assumptions:

- The interaction of the rotor disk and the fluid flow through it can be computed by the hydrodynamic forces that each radial section of the blade exert on the fluid. These forces can be calculated from 2D measurements or simulations of airfoil sections under varying Reynolds numbers and angles of attack. The actual values used for the Blade Element Model are interpolated from the values existing in the table.
- The forces exerted by each blade element at a radial position can be added over the entire revolution and multiplied by the number of blades to provide an average of the force over an entire rotor revolution. Thus, an intrinsically unsteady problem of the force applied by each blade element on the fluid as the blade rotates is converted into an steady (in the rotationally-averaged sense) problem where the forces are spread across the entire radial ring that the blade elements cover in their rotation and applied steadily in time.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

The Blade Element Model was used in simulations of turbine and array domains that required medium sensitivity to turbine parameters and allow for intermediate turn over of results. Typical simulations used computational grids with 1 Million<N<10 Million cells and provided results within 10-100 hours of computer clock time. Accuracy was expected to match efficiency within 2% of experimental or higher resolution model results, with wake velocity profile matching results within 5% at locations 1.5 rotor diameters behind the turbine.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Numerical Simulations of single turbine and small arrays were conducted to validate this model. Performance was documented in the following publications:

Javaherchi, T. (2010). Numerical Modeling of Tidal Turbines: Methodology Development and Potential Physical Environmental Effects. Master's thesis, University of Washington.

Javaherchi, T., A. Aliseda. (2010). Numerical Modeling of Hydrokinetic Turbines and their Environmental Effects. *APS 63rd DFD Meeting*. Long Beach, CA.

Javaherchi, T., A. Aliseda, S. Antheaume, J. Seydel, B. Polagye. (2009). Study of the turbulent wake behind a tidal turbine through different numerical models. *APS 62nd DFD Meeting*. Minneapolis, MN.

IJavaherchi, T., N. Stelzenmuller, A. Aliseda. (2014). Experimental and Numerical Analysis of a Scale-Model Horizontal Axis Hydrokinetic Turbine *2nd Marine Energy Technology Symposium.* Seattle, WA.

Stelzenmuller, N., and A. Aliseda. (2012). An experimental investigation into the effect of Marine Hydrokinetic (MHK) turbine array spacing on turbine efficiency and turbine wake characteristics. *APS 65th DFD Meeting*. San Diego, CA.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

The Blade Element Model uses airfoil theory to discretize the turbine blades into elements that exert a force on the surrounding fluid equal and of opposite sign to the lift and drag experienced by the blade element due to its relative motion with respect to the flow. The rotor design is taken into account by the drag and lift coefficient tables associated with the airfoils used in the construction of the blades, and in the number of blades, as the force on each blade section is multiplied by the number or blades and then distributed uniformly along the annular area swept by that blade element in its rotation.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

The Blade Element Model uses theoretical developments originally conceived to study airplane propellers and helicopter rotors in the 1920-40s (Glauert, H. 1926. "The Analysis of Experimental Results in the Windmill Brake and Vortex Ring States of an Airscrew." ARCR R&M No. 1026., Glauert, H. 1926. "A General Theory of the Autogyro." ARCR R&M No. 1111., Glauert, H. 1935. "Airplane Propellers." Aerodynamic Theory, W. F. Durand, ed., Div. L, Chapter XI. Berlin:Springer Verlag.). The evolution of the theory can be followed in the review by Leishman (Leishman, J.G. 2000. Principles of Helicopter Aerodynamics. Cambridge University Press, pp. 78-127.) Application to Horizontal Axis Wind Turbines and subsequently to Horizontal Axis Hydrokinetic Turbines can be found in the late 1990s and 2000s (J. N. Sorensen, W.Z. Shen, *J. 2002,* “Numerical Modeling of Wind Turbine Wakes”, *Fluids Eng* 124(2), 393-399., T. Javaherchi, S. Antheaume, A. Aliseda 2014 “Hierarchical methodology for the numerical simulation of the flow field around and in the wake of horizontal axis wind turbines: Rotating reference frame, blade element method and actuator disk model” Wind Engineering 38 (2), 181-201)

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

This formulation has been used for almost a century in the aerospace field. The use in axial flow wind turbines, and subsequently on Horizontal Axis Hydrokinetic Turbines extends for over 30 years. It has resulted in hundreds of peer-reviewed publications that reference and expand over the original mid 20th century formulation.

- Vortex shedding, an intrinsically unsteady phenomenon, is not adequately modeled, and the blade tip vortex that characterizes the outer region of the near wake is represented by a vortex crown instead of a vortex helix.

- Nacelle interactions are not well represented as the flow in the root are of the blade, near the nacelle is frequently detached and therefore not well represented by the drag and lift coefficient tables used in the BEM. Additionally, counter-rotating (with respect to the rotor) vortices shed by the nacelle strongly influence the determination of the local angle of attack at the blade root. Inaccuracies in computing these flows result in errors in the angle of attach propagate into the detached region of the blade and the nacelle vortices. The BEM disk can be truncated into a ring with the inner region (the hole inside the BEM rotor “donut”) represented by a drag force (nacelle drag) or by the actual geometry of the nacelle. This last option, however, presents numerical challenges as the discretization required by the representation of the boundary layer on the nacelle walls is highly incompatible with the BEM rotor disk discretization, and the discontinuity at the inner surface of the BEM ring presents instabilities that can make convergence and stability difficult in the region of the blade root/nacelle boundary layer.

HARDWARE REQUIREMENTS

BEM can be run on any medium-size desktop server with modern RAM and CPU capabilities. For the purposes of the simulations conducted in this project, different servers with 16-32 cores and 64-96 Gb of RAM were used. Fluent v14 was the computational platform of choice. More information about the requirements for Fluent v14 and the BEM implementation within it can be found in the users manual.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

Hansen, A, C. Butterfield. (1993). Aerodynamics of horizontal-axis wind turbines. *Annual Review of Fluid Mechanics.*

Manwell, J.,McGowan, A. Rogers. (2002). *Wind Energy Explained. Theory, Design and Application*. John Wiley and Sons, Ltd.

Walker, J., N. Jenkins. (1997). *Wind Energy Technology*. JohnWiley and Sons, Ltd.

MODEL RELATED TO DELIVERABLE 12.1.1

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

A time-domain model of point absorber WECs with arbitrary geometry was developed. Additionally, a hydraulic PTO model was developed and integrated with the point absorber model. These models were documented in:

Ruehl K. (2011.) Time Domain Modeling of Heaving Point Absorber Wave Energy Convertors, Including Power Take-Off and Mooring. Master's thesis, Oregon State University.

This work formed the foundation for Ruehl's later work at Sandia on WEC-Sim.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

See Ruehl's Master's thesis.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Single body geometry was validated by wave tank testing. See Ruehl's Master's thesis.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

The methodology uses the geometry's unique frequency-domain hydrodynamic response to determine the point absorber's time-domain impulse response functions. By implementing the point absorber's impulse response functions, time-domain equations of motion are defined and the WEC's heave displacement and velocity are solved for in a WEC Dynamics Model developed in MATLAB/Simulink.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

See Ruehl's Master's thesis.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

The model was documented in the following peer-reviewed publications:

Ruehl K., B. Paasch, T.K.A. Brekken, B. Bosma. (2013). Wave energy converter design tool for point absorbers with arbitrary device geometry. *International Ocean and Polar Engineering Conference* (ISOPE). Anchorage, AK.

Ruehl K., T.K.A. Brekken, B. Bosma, R. Paasch. (2010). Large-Scale Ocean Wave Energy Plant Modeling. IEEE *Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply*. Boston, MA.

HARDWARE REQUIREMENTS

Computer running MATLAB/Simulink.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

See Ruehl’s Master’s thesis.

MODEL RELATED TO DELIVERABLE 12.1.2

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

A time-domain hydraulic PTO model was developed, along with a linear quadratic tracking controller model. Passive and active control strategies were compared. These models were documented in:

Casey S. (2013). Modeling, Simulation, and Analysis of Two Hydraulic Power Take-off Systems for Wave Energy Conversion. Master's. thesis, Oregon State University.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

See Casey's Master's thesis.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Physical validation was not conducted.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

See Casey's Master's thesis.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

See Casey's Master's thesis.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

The model was documented in the following peer-reviewed publication:

Casey S., B. Batten, R. Paasch. (2013). Comparison of passive and active controlled hydraulic power take off systems for wave energy conversion. *1st Marine Energy Technology Symposium*. Washington, DC.

HARDWARE REQUIREMENTS

Computer running MATLAB/Simulink.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

See Casey's Master's thesis.

MODEL RELATED TO DELIVERABLE 14.1.1

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

The model produces a high-resolution time-series output of wave park (i.e., array) power.

The model assumes no interaction between WECs. Any regularly spaced array of WECs can be used: any number in the x and y direction, so long as they are regularly spaced.

The intended use is to generate power time series for use in power systems integration studies. The focus is on capturing the short and long term variability of power output for studying flicker and power quality. The focus is not precise hydrodynamic simulation.

No energy storage is assumed.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

Any regularly spaced array of WECs can be used: any number in the x and y direction, so long as they are regularly spaced.

The model takes NDBC buoy data as an input and generates a wave energy converter array power output at a 0.5 second resolution.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

The model has not been validated as actual wave park output is not available.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

Simple wave-follower theory is used. In other words, it is assumed the WEC follows the water surface elevation and that WEC speed is equal to the water surface elevation vertical speed. Power is assumed to be proportional to the square of speed.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

All mathematics are documented in

Brekken T.K.A., T. Ozkan-Haller, A. Simmons. (2012). A methodology for large-scale ocean wave power time-series generation. *IEEE Journal of Oceanic Engineering*. Vol. 37, no. 2, pp. 294–300.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

The formulation was peer reviewed in

Brekken T.K.A., T. Ozkan-Haller, A. Simmons. (2012). A methodology for large-scale ocean wave power time-series generation. *IEEE Journal of Oceanic Engineering*. Vol. 37, no. 2, pp. 294–300.

Strengths are generated the aggregated output of many hundreds of wave energy converters simultaneously. Weakness are no inclusion of WEC hydrodynamics or body-body interactions.

HARDWARE REQUIREMENTS

None.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

Brekken T.K.A., T. Ozkan-Haller, A. Simmons. (2012). A methodology for large-scale ocean wave power time-series generation. *IEEE Journal of Oceanic Engineering*. Vol. 37, no. 2, pp. 294–300.

MODEL RELATED TO DELIVERABLE 14.2.3

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

This study developed computer codes to determine a stable static equilibrium configuration of slack moored submerged bodies. These bodies represent hydrokinetic turbines that are moored in deep water. Some contributions of the work done include: (i) the use of a Lagrangian mechanics framework to model the system; (ii) the treatment of the mooring line slackness and sea floor impenetrability as non-holonomic (inequality) constraints; and (iii) considering a network of possibly redundant mooring lines (i.e., some mooring lines may be completely slack).

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

The code is required to solve static equilibrium configuration for a network of 50 slack moored turbines in under 30 minutes.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

The simulation codes are validated by comparing computed results with analytical results for (i) an elastic catenary, (ii) a single-point moored buoy, and (iii) a three-point moored buoy. In all cases the computer codes produced results that are within 2% of the analytical solutions.

DuBuque G. (2011). A Lumped Parameter Equilibrium Model of a Submerged Body with Mooring Lines. Master's thesis, University of Washington.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

The moored system is modelled as follows.

Rigid bodies: Each body is modelled using six-degrees of freedom, i.e., three translational and three rotational degrees of freedom.

Mooring lines: The mooring lines are modeled as unidirectional elastic springs (i.e., the mooring lines are allowed to be slack). Each mooring line can be divided into an arbitrary number of segments. Moreover, the mooring lines can be combined to form a network.

System loads: The effects of the weight and buoyancy of each inertial element are accounted for in the equilibrium equations. Also included are the effects of lift and drag on the system elements due to fluid motion. Additionally, the fluid velocity is assumed to have spatial variation.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

A Lagrangian mechanics framework is used to construct the equilibrium condition which takes the form of a system on nonlinear equations that contain inequality constraints. These constrained nonlinear equations are solved using a sequential quadratic programming technique that minimizes the exact L_1 penalty function.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

Fabien B.C. (2012). Equilibrium of submerged bodies with slack mooring. In Nonlinear *Approaches in Engineering Applications*. L. Dai and R. L. Jazar, (Eds.) Springer-Verlag.

The work sited above is limited to the study of static problems and cannot be used to evaluate the behavior of the moored system in rapidly changing fluid flows (or sea states).

HARDWARE REQUIREMENTS

Any computer capable of running MATLAB version 2015a or Octave 3.0.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

Code and examples: http://abs-5.me.washington/mhksim/src/

Single-point mooring: http://abs-5.me.washington/mhksim/src/test0.m

Three-point mooring: http://abs-5.me.washington/mhksim/src/test1.m

Network of 14 turbines: http://abs-5.me.washington.edu/mhksim/src/test_mm0.m

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

The model is a semi-analytical estimate for the probability that received levels of sound produced by a tidal turbine will be detectable by a class of marine animal based on the probability of co-temporal ambient noise and animal hearing thresholds. The model is implemented in Matlab and intended for environmental assessment. An early formulation of this model was used to structure marine mammal and acoustic monitoring plans for Snohomish PUD's tidal energy demonstration project.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

The model is intended to provide context for environmental assessments and monitoring of the effects of underwater sound produced by tidal turbines. To achieve this, it employs a series of transparent assumptions that yield a semi-analytical estimate for the probability of sound detection. The model relies heavily on the availability of input data, specifically, empirical estimates for the time-varying characteristics of frequency-dependent turbine sound and ambient noise.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Ambient noise inputs were developed based on field data from Admiralty Inlet, Puget Sound, Washington. Model validation was an aspect of environmental monitoring plans for the Snohomish PUD tidal energy demonstration project. Since that project is not moving forward, no model validation data (i.e., measurements of turbine sound) at this location are anticipated in the near future. Upcoming (spring 2017) turbine sound playback studies may provide an opportunity for model validation.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

For turbine sound to be detected at a particularly location, frequency-specific received levels must exceed ambient levels and animal hearing thresholds. Turbine received levels depend on source levels (assumed to be dependent solely on current velocity) and transmission loss (assumed to be primarily a function of distance from source to receiver, using a practical spreading approximation). Ambient noise levels depend on current velocity at frequencies > 1 kHz due to the mobilization of sediments (e.g., cobbles, gravel) by currents and are independent of current velocity at frequencies < 1 kHz.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

The probability of sound detection (*d*) as a function of position in space (*x*, *y*, and *z*) and frequency (*f*) can be described as

$$p\left(d_{x,y,z,f}\right)=\sum_i\left(\sum_j d\left(NL_j,RL_i,HT\right)p\left(NL_j\middle|RL_i\right)\right)p\left(RL_i\right).$$

Detection is a binary function of noise level (*NL*), received level (*RL*), and hearing threshold (*HT*). This is multiplied by the conditional probability of a noise level given a received level (related by current velocity for frequencies > 1 kHz) and summed over all probable noise levels. This intermediate detection probability is then multiplied by the probability of a received level occurring (i.e., probability of current speed occurring) and summed over all possible received levels.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

The current model was submitted for peer review to the IEEE Journal of Oceanic Engineering as:

Polagye B., C. Bassett, M. Holt, J. Wood, S. Barr. A framework for detection of tidal turbine sound: A pre-installation case study for Admiralty Inlet, Puget Sound, Washington (USA). Submitted to *IEEE Journal of Oceanic Engineering*.

Of the received reviews, one felt that the model provided an excellent tutorial on the nuances of animal detection of turbine sound beyond the behavioral thresholds applied in regulatory consultation in the US, one felt that the model had merit but required a parabolic equation representation of transmission loss to be valid (rather than a practical spreading model), and the third felt that the work had no merit (and did not read beyond the introduction of the manuscript to draw this conclusion). Submission of a revised manuscript has been pending publication of turbine sound data and completion of parabolic equation modeling for transmission loss.

HARDWARE REQUIREMENTS

The code runs within an hour on a high-end workstation.

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

Documentation of the alpha version is provided in-line with the code.

MODEL DESCRIPTION, KEY ASSUMPTIONS, VERSION, SOURCE AND INTENDED USE

The specific model for electrochemical reaction + transport developed for the present work was developed using the commercial COMSOL Multiphysics as the computational platform. For this project, COMSOL Multiphysics 4.4 was used.

COMSOL Multiphysics is a numerical Finite Element Analysis platform that can be used to model and simulate physical systems, including coupled phenomena, such as those involving electrical, mechanical, fluid flow, and chemical reactions. The software includes pre-defined sets of equations describing material properties, boundary conditions, source and/or sink terms, and custom sets of partial differential equations (PDEs) as needed to define the model under analysis.

In the present model the coupled phenomena were:

- Local electrical potential at the electrode surface
- Local electrochemical reaction rate (chloride oxidation to ClO^-) from measured Tafel parameters for the carbon based foul prevention coatings
- Local concentration of Cl^- and ClO^-
- Transport of Cl^- and ClO^- to/from surface by diffusion and advection

The intended use of the model is to deconvolute the effect of reactor kinetics such as transport of reactants through seawater, or secondary electric potential losses in the electrode, from chemical reaction kinetics from the overall experimentally observed reaction rates.

PERFORMANCE CRITERIA FOR THE MODEL RELATED TO THE INTENDED USE

For use in this project a 2D model including the electrode surface and a thin section of a semi-infinite reservoir of sea water experiencing laminar flow at the electrode surface was modelled. The optimization of the model (extracted reaction rates and local concentrations of ClO^- in the Prandtl boundary layer) was based on the observed and calculated current flow for identical transport and electrical conditions. The model was optimized iteratively on a Goodness of Fit (GooF) cost function until the change in GooF was less than 0.1%.

TEST RESULTS TO DEMONSTRATE THE MODEL PERFORMANCE CRITERIA WERE MET (E.G., CODE VERIFICATION, SENSITIVITY ANALYSES, HISTORY MATCHING WITH LAB OR FIELD DATA)

Results of the model under various seawater flow rates and applied electrical potentials were determined, with self consistent results. This was documented in the following PhD dissertation:

B Bunn, M. (2015). Aging and Performance Evaluation of Marine Antifouling Coatings. Master’s Dissertation. Oregon State University.

THEORY BEHIND THE MODEL, EXPRESSED IN NON-MATHEMATICAL TERMS

The local concentration of hypochlorite at the surface of the biofouling prevention coating (the working electrode) is a function of rate of chemical reaction, as dependent on the local concentration of chloride and previously generated hypochlorite; the applied electrical potential, which may have been affected by either losses as current flows through the working electrode or inhomogeneities in electrical potential between the working electrode and the counter-electrode; the electrocatalysis parameters for the working electrode as determined from Tafel scans of the electrode material; and the advective transport of the reactants from the flow of seawater through the system.

MATHEMATICS TO BE USED, INCLUDING FORMULAS AND CALCULATION METHODS

The model is based upon a well accepted set of equations and boundary conditions, and COMSOL a well accepted computational platform built upon a finite element analysis solver for all the physics described above.

WHETHER OR NOT THE THEORY AND MATHEMATICAL ALGORITHMS WERE PEER REVIEWED, AND, IF SO, INCLUDE A SUMMARY OF THEORETICAL STRENGTHS AND WEAKNESSES

The use of COMSOL to solve coupled chemical + transport reaction systems, including electrochemical reaction systems, is well documented in the technical literature. A search of the single journal "Chemical Engineering Journal" yields 101 papers in chemical reaction literature for the years 2008 to the present. Our lab has used it successfully for similar purposes for other past and ongoing projects.

HARDWARE REQUIREMENTS

Commercial versions of COMSOL Multiphysics can be acquired from COMSOL, Inc. as documented at https://www.comsol.com/

DOCUMENTATION (E.G., USERS GUIDE, MODEL CODE).

A user's guide to the use of COMSOL for various process simulations can be found at http://cdn.comsol.com/documentation/5.2.0.220/IntroductionToCOMSOLMultiphysics.pdf

The model itself employed in the work is contained in file MicroRXModel.mph

FACULTY FUNDED THROUGH THIS PROJECT

Faculty/Staff Member	Area/University	Specialization
Roberto Albertani	Mechanical Engineering, OSU	Composites, Off-shore Wind Energy
Alberto Aliseda	Mechanical Engineering, UW	Hydrodynamics: Experimental and Computational
Ean Amon*	Electrical Engineering, OSU	Power Systems; Test Engineer
Belinda Batten	Mechanical Engineering, OSU	Modeling and Control of Devices and Arrays
George Boehlert**	Hatfield Marine Science Center, OSU	Environmental Research Director (2008-2012)
Ted Brekken	Electrical Engineering, OSU	Modeling and Control of Devices and Arrays; Power Systems
Flaxen Conway	Marine Resource Management, OSU	Communication Engagement, Human Dimensions Research
Brian Fabien	Mechanical Engineering, UW	Dynamics and Control: Mooring System Analysis
Merrick Haller	Civil Engineering, OSU	Wave Resource Characterization; Scaled Testing; Device and Array Effects
Joe Haxel	Hatfield Marine Science Center, OSU	Passive Acoustic Modeling, Analysis and Testing
Sarah Henkel	Hatfield Marine Science Center, OSU	Benthic Ecology, Environmental Research Director (2013-present)
Kaety Jacobson	Oregon Sea Grant	Community Engagement, Fisheries Specialist
Mitsuhiro Kawase**	Oceanography, UW	Effects of Energy Removal from Estuarine Ecosystems
Phil Malte	Mechanical Engineering, UW	Modeling and Control of Devices and Arrays
Michael Motley	Civil Engineering, UW	Fluid-structure Interactions for Turbine Blades

Tuba Ozkan-Haller	Oceanography, OSU	Wave Resource Characterization; Scaled Testing; Device and Array Effects
Robert Paasch	Mechanical Engineering, OSU	Device and PTO Design, Reliability and Survivability
Brian Polagye	Mechanical Engineering, UW	Tidal Resource Characterization, Environmental Effects
Jim Riley	Mechanical Engineering, UW	High-resolution Oceanographic Simulation
Adam Schultz	Oceanography, OSU	Electro-magnetic Field Modeling, Analysis, Testing
Rob Suryan*	Hatfield Marine Science Center, OSU	Seabird Ecologist
Jim Thomson	Civil Engineering and Applied Physics Laboratory, UW	Hydrodynamic Measurements, Instrumentation Platform Development
Mark Tuttle	Mechanical Engineering, UW	Durability of Composite Materials
Annette von Jouanne	Electrical Engineering, OSU	Power Systems, Device Design, MOTB team leader
Solomon Yim	Civil Engineering, OSU	Computational Fluid-Structure Interaction Modeling
Alex Yokochi	Chemical Engineering, OSU	Biofouling; Reliability and Survivability of Materials

*no longer employed by OSU

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