# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix A: Deliverables for Tasks: 1, 7, 13**
***Advanced Wave Forecasting Technologies***

**DOE Award Number: DE-FG36-08GO18179-M001**
**Period Covered: 9/15/2008 – 3/14/2016**
**Delivered: June 30, 2016**

**Oregon State University**
**University of Washington**

## Deliverables



## Deliverable 1.1: Initial simulations with physics-based near shore wave model

An operational inner-shelf wave forecasting system was implemented for the Oregon and southwest Washington coast in the U.S. Pacific Northwest (PNW). High-resolution wave forecasts are useful for navigational planning, identifying wave energy resources, providing information for site-specific coastal flood models, and having an informed recreational beach user group, among other things. This forecasting model is run once a day at 1200 UTC producing 84-hour forecasts.

The WAVEWATCH III v3.14 is the physics-based numerical model implemented in this project. This is a third-generation phase-averaged wave model developed by the National Centers for environmental Prediction (NCEP) that solves the spectral wave action balance equation (Garcia-Medina et al., 2013). This operational forecasting model provides 84-h forecasts at a 30-arc-second resolution. At this resolution the model provides 510 output points along the Oregon coastline and enables the generation of a high-resolution wave climate database. Garcia-Medina et al. describes all the tests that were performed to the forecasting model to assess its accuracy. In addition, taking advantage of the model implementation we describe the dominant wave transformation processes in the Oregon shelf and describe the large scale patterns of variations in the wave conditions. The bulk of this work was done between September 2009 and June 2012. In addition to the methodology described in the previous publication we performed controlled numerical experiments implementing another open source numerical wave model (SWAN) to complement Wavewatch III.

### Related Publications

Garcia-Medina G., Ozkan-Haller H.T., Ruggiero P. and Oskamp J. (2013). An Inner-Shelf Wave Forecasting System for the US Pacific Northwest. *Weather and Forecasting.* Vol. 28(3), pp. 681-703. http://hdl.handle.net/1957/41661

## Deliverable 7.1: Simulations over the OR shelf with physics-based model and assessment of forecast accuracy with in-situ and wave radar observations

We compared model results with available in situ wave data within the region covered by our high-resolution domains. We had access to intermediate to shallow water wave data collected during three field experiments. Two deployments used Acoustic Wave and Current sensors (AWAC) to measure wave activity. These sensors track the water surface and particle velocity, and these data were converted to wave spectral information by making use of linear wave theory. The RP09 deployment covered a period from 18 September to 2 December 2009.

*Nearshore wave predictions along the Oregon and southwest Washington coast* addresses the initial implementation a high resolution wave forecasting system for the coast of Oregon and southwest Washington. The model accuracy is discussed by comparing our implementation with wave measurements in the continental shelf. The bulk of this work was done from September 2010 to December 2011. Our methodology can be summarized chronologically as follows:

- Obtained and implemented the Wavewatch III model from NOAA.
- Collected wave measurements in the region.
- Optimized the model domains for the study area.
- Made data-model comparisons
- Implemented the forecasting model.

### Related Publications

Garcia-Medina G., H.T. Ozkan-Haller, P. Ruggiero. (2012). Nearshore wave predictions along the Oregon and southwest Washington coast. *33rd International Conference on Coastal Engineering*. Santander, Spain.

## Deliverable 7.2: Incorporation of ANN analysis to correct forecast errors from physics-based model

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

Parkinson et al. analyzes available input data sources and compares methods for predicting regional-scale wave power schedules over short-term planning horizons. We compared a hybrid statistical forecasting method that combines regressions and neural networks to a simpler physics based approach. The methodologies were applied to generate wave power forecasts over horizons ranging from 15-min to 6 h.

To examine implications of geographic diversification, forecasts were generated from spatially-aggregated data.

### Related Publications

Parkinson S.C., K. Dragoon, G. Reikard, G. García-Medina, H.T. Özkan-Haller, T.K.A. Brekken. (2015). Integrating ocean wave energy at large-scales: A study of the US Pacific Northwest Renewable Energy. *Renewable Energy*. Vol.76, pp.551-559.

## Deliverable 13.1: Routine wave power forecasts to aid in design and implementation of test berth

Routine Wave measurements and forecasts are available online at the Northwest Association of networked Ocean Observing Systems (NANOOS). NANOOS is a part of the National Oceanographic and Atmospheric Association (NOAA), and aggregates ocean and coastal data and forecast model from around the Pacific Northwest (PNW). NANOOS maintains a website at http://www.nanoos.org/ where results from forecast models or observation stations can be visualized.

The Maritime operations tool within NANOOS clearly labeled OSU Wave Forecasts which can be accessed by the public. These forecasting systems provide predictions concerning wave height and wave period along the PNW coastline. This information can be found at http://nvs.nanoos.org/MaritimeOps on the 'models' menu. Detailed information at nearshore points along the 20m bathymetric contour (including spectral wave information) can be accessed by selecting the nodes indicated by yellow bullets. This system has been operating since 2011.

## Deliverable 13.2: Assessment of total errors associated with hybrid (physics/ANN) technique

Garcia-Medina et al. (2014) addresses a regional assessment of the wave energy resource. Building upon the implemented and validated numerical models for the region, we performed a 7-year hindcast to describe the wave energy distribution in the shelf. We stored model output at locations where we had access to wave measurements and at 4 major isobaths along the shelf. These time series were used to evaluate the wave energy resource and have also been used by other research groups. The majority of this work was done between May 2012 and May 2013.

*Wave-by-wave Forecasting of Sea Surface Elevation for WEC Applications Utilizing NARX Neural Networks* discusses forecasting of ocean waves over a short duration on the order of tens of seconds was approached with the optimization of wave energy conversion in mind. This study outlines the development of an artificial neural network model, specifically the Nonlinear Autoregressive Network with Exogenous Input (NARX), to predict a wave-by-wave surface elevation time series based entirely on previous observations at the site of interest. Such a model would be computationally less intensive than competing deterministic techniques rooted in wave theory but would have a shorter prediction horizon when compared to physics-based models developed under Garcia-Medina et al. and funded through NNMREC.

## Related Publications

Garcia-Medina G., H.T. Ozkan-Haller, P. Ruggiero, J. Oskamp. (2013). An Inner-Shelf Wave Forecasting System for the US Pacific Northwest. *Weather and Forecasting*. Vol. 28(3), pp. 681-703. http://hdl.handle.net/1957/41661

Garcia-Medina G., H.T. Ozkan-Haller, P. Ruggiero. (2014). Wave energy resource characterization in Oregon and Southwest Washington. *Renewable Energy*. 64, pp. 203-214.

Gillespie, A. (2015). Wave-by-wave Forecasting of Sea Surface Elevation for WEC Applications Utilizing NARX Neural Networks. Master's thesis, Oregon State University. http://hdl.handle.net/1957/57966

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix B: Deliverables for Tasks: 2, 8, 14**
***Device and Array Optimization***

**DOE Award Number: DE-FG36-08GO18179-M001**
**Period Covered: 9/15/2008 – 3/14/2016**
**Delivered: June 30, 2016**

**Northwest National Marine Renewable Energy Center**

**Oregon State University**
**University of Washington**

## Deliverables

## Deliverable 2.1.1: A coupled fluid-structure interaction model for prediction of near-field dynamics of a single WEC device

Knowledge of wave conditions in nearshore regions supports the development of ocean wave energy technology by providing wave climatology for device design considerations, and power output estimates. By modeling wave transformation over the continental shelf, wave conditions were predicted in nearshore regions where potential wave energy conversion sites are located. Subsequently, a wave-structure interaction model was implemented, and power output estimates were made for a simplified wave energy converter operating in measured spectral wave conditions. For the purpose of modeling wave transformation, the SWAN spectral wave model was applied to three domains on Oregon's continental shelf. The purpose was to assess the skill of the SWAN model in this application (highly energetic waves on a narrow continental shelf).

By comparing results with in situ data collected near the coast, it was found that the model had substantial skill, predicting in situ wave heights with RMS percent errors of 11%. The characterization of the transformation across the shelf was not improved by including bottom friction and wind wave generation, suggesting that these physical processes are not important for a model of Oregon's continental shelf considering depths less than 150m. When basin scale wave model output was used to force the outer shelf boundary, the model remained skillful, with RMS percent errors of 17-20% (Oskamp, 2011). In order to estimate power output from a wave energy converter, device response to hydrodynamic forces was computed using the WAMIT boundary element method, potential ow model. A method was outlined for using the hydrodynamic response to estimate power output. This method was demonstrated by considering an idealized non-resonating wave energy converter with one year of measured spectral wave conditions from the Oregon coast.

### Related Publications

Garcia-Medina G., H.T. Ozkan-Haller, P. Ruggiero, J. Oskamp (2013). An Inner-Shelf Wave Forecasting System for the U.S. Pacific Northwest. *Weather and Forecasting*, Vol. 28(3), pp. 681-703.

McNatt J.C. (2012). Wave field patterns generated by wave energy converters. Master's thesis, Oregon State University. http://hdl.handle.net/1957/33939

Oskamp J. (2011). Toward wave energy in Oregon predicting wave conditions and extracted power. Master's thesis, Oregon State University. http://hdl.handle.net/1957/21784

## Deliverable 2.1.2: A near shore wave model for the test berth site, incorporating a simplified representation of WEC devices, with testing as wave observations come online

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 Technology. 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 device locations, based on the experimentally determined Power Transfer Function.

### Related Publications

O'Dea A. (2014). On the nearshore impact of wave energy converter arrays. Master's thesis. Oregon State University. http://hdl.handle.net/1957/52599

O'Dea A.M., M.C. Haller (2014). Analysis of the impacts of wave energy converter arrays on the nearshore wave climate. *2nd Marine Energy Technology Symposium*. Paper#112. Seattle, WA, http://vtechworks.lib.vt.edu/bitstream/handle/10919/49231/112-ODea.pdf?sequence=1&isAllowed=y

## Deliverable 2.1.3: An initial fluid/structure interaction module for motion of WEC device and local flow properties

A comprehensive approach to analytical and numerical wave models on coupled fluid-structure interaction for WEC device were developed and field tests were conducted in this project. To fully understand the physics of wave loads on WEC devices especially due to impact, physical model tests in the large-scale wave-basin environment was also a major focus. 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 device. Two commercial software, AQWA and LS-DYNA, were also employed. Fundamental development on the potential theory was performed by Dr. Nimmala, a former PhD student on the project (see Nimmala, Yim and Grilli (2012, 2013)), and viscous flow and coupling between potential and viscous flow by Dr. Zhang, another former PhD student on the project (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 were described in Zhang and Yim (2015a) and data analysis in Zhang and Yim (2015b & c). Because there are no available measurements of wave impact on WEC devices, 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 by Dr. Challa, a former PhD student on the project, were found to be able to predict the peak pressure well (see Challa et al. 2010a & b, and 2014a & b, Zhang et al 2015).

## Related Publications

Challa R., V.G. Idichandy, C.P. Vendhan, S.C. Yim. (2010). An Experimental Study on Rigid-Object Water-Entry Impact and Contact Dynamics. *Offshore Mechanics and Arctic Engineering Conference*. Shanghai, China. Paper No. OMAE2010-20658.

Challa R., S.C. Yim, V.G. Idichandy, C.P. Vendhan. (2010). Finite-Element and Smoothed Particle Hydrodynamics Modeling of Rigid-Object Water-Entry Impact Dynamics and Validation with Experimental Results. *Offshore Mechanics and Arctic Engineering Conference*. Shanghai, China. Paper No. OMAE2010-20659.

Challa R., S.C. Yim, V.G. Idichandy, C.P. Vendhan. (2014). Rigid-Object Water-Surface Impact Dynamics: Finite-Element/Smoothed Particle Hydrodynamics Modeling and Experimental Calibration. *Offshore Mechanics and Arctic Engineering*. ASME. Vol.136, No.2, doi: 10.1115/1.4027454, pp.1-12.

Challa R., S.C. Yim, V.G. Idichandy, C.P. Vendhan. (2014). Rigid-Object Water-Surface Impact Dynamics: Experiment and Semi-Analytical Approximation. *Offshore Mechanics and Arctic Engineering*. ASME. Vol.136, No.1, doi: 10.1115/1.4025653, 011102, pp.1-10.

Nimmala S.B., S.C. Yim, S.T. Grilli. (2012). An Efficient 3-D FNPF Numerical Wave Tank for Virtual Large-Scale Wave Basin Experiment. *Offshore Mechanics and Arctic Engineering Conference*. Rio de Janeiro, Brazil. Paper No. OMAE2012-83760. http://hdl.handle.net/1957/59049

Nimmala S.B., S.C. Yim, S.T. Grilli. (2013). An Efficient Parallelized 3-D FNPF Numerical Wave Tank for Large-Scale Wave Basin Experiment Simulation. *Offshore Mechanics and Arctic Engineering*. ASME. Vol 135, doi:10.1115/1.4007597, pp.10.

Zhang Y., F. Del Pin and S.C. Yim. (2014). A Heterogeneous Flow Model Based on DD Method for Free-Surface Fluid-Structure Interaction Problems. *International Journal of Numerical Methods in Fluids*. Vol.74, pp.292-312, doi:10.1002/fld.3852.

Zhang Y., A. Mohtat, S.C. Yim. (2015). Effect of Compressibility on Pressure during Water Entry of a Wedge. *Offshore Mechanics and Arctic Engineering Conference*. St. Johns, Canada. OMAE2015-41702.

Zhang Y., M. Peszynska, S.C. Yim. (2013). Coupling of Viscous and Potential Flow Models with Free Surface for Near and Far Field Wave Propagation. *International Journal of Numerical Analysis and Modeling*. Series B, Vol.4(3), pp.256-282.

Zhang Y., S.C. Yim. (2015a). A POD–Based Method for Low–Dimensional Components of Free/Moving Surface Flows. *Offshore Mechanics and Arctic Engineering Conference*. St. Johns, Canada.

Zhang Y., S.C. Yim. (2015b). Proper Orthogonal Decomposition of Pressure Field in Sloshing Impact. *ASCE Engineering Mecha*nics. Vol.141(9), doi.10.1061/(ASCE)EM.1943-7889.0000924, pp.1-22.

Zhang Y., S.C. Yim. (2015c). Solitary wave breaking on irregular 3D bathymetry using a coupled potential + viscous flow model. *ASCE Engineering Mechanics*. Vol.141(6), doi.10.1061/(ASCE)EM.1943-7889.0000894, 04014171, pp.1-16.

Zhang Y., S.C. Yim, Del Pin F. (2015). A Non-Overlapping Heterogeneous Domain Decomposition Method for Three-Dimensional Gravity Wave Impact Problems. *Computer and Fluids*. Vol.106, dx.doi.org/10.1016/j.compfluid.2014.09.005, pp.154-170.

## Deliverable 2.1.4: An initial generalized control model

The generalized control model is a mathematical definition of wave energy converters that can be applied to a broad range of modeling and control problems. The first approach is a linear model and is fast to compute and compatible with the rich range of options for estimation and control of linear systems. The model is particularly well described in (Brekken 2011), and in a forthcoming paper by Starrett et al on Model Predictive Control of multibody systems.

### Related Publications

Bosma B., T.K.A. Brekken, H.T. Ozkan-Haller, S. Yim. (2013). Wave energy converter modeling in the time domain: a design guide. *IEEE Conference on Technologies for Sustainability (SusTech)*. Portland, OR. pp. 103–108. http://hdl.handle.net/1957/59053

Bosma B., Z. Zhang, T.K.A. Brekken, H.T. Ozkan-Haller, C. McNatt, S. Yim. (2012) Wave energy converter modeling in the frequency domain: A design guide. *Energy Conversion Congress and Exposition (ECCE)*. pp. 2099–2106.

Brekken T.K.A., B. Batten, E. Amon. (2011). From blue to green [ask the experts]. *IEEE Control Systems Magazine*. Vol. 31, pp. 18–24.

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

Richter M, M. Magana, O. Sawodny, T.K.A. Brekken. (2014). Power optimisation of a point absorber wave energy converter by means of linear model predictive control. *IET Renewable Power Generation*. Vol. 8, pp. 203–215.

Starrett M., R. So, T. K. Brekken, A. McCall. (2015). Development of a state space model for wave energy conversion systems. *Power Energy Society General Meeting.* IEEE. pp. 1–5.

## Deliverable 2.2.1: An initial numerical model of wakes and flow redirection.

Turbine modeling work was conducted under the standardized rotor geometry of the NREL Phase VI wind turbine. Several rotor and turbulence closure models were investigated and the accuracy and computational efficiency of each one to correctly predict the features of the turbine wake: momentum deficit, energy extraction, blade tip vortex extend and persistence, rotational component in the wake, hub vortex, etc., was determined. The work was implemented on ANSYS Fluent, the leading commercial software package for Computational Fluid Dynamics.

Javaherchi and Aliseda 2009. 2010. 2010a, 2010b, 2010c, describe the simulation efforts, starting 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 that was created based on the NREL Phase VI wind turbine 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.

### Related Publications


Javaherchi, T. (2010). Numerical Modeling of Tidal Turbines: Methodology Development and Potential Physical Environmental Effects. Master's thesis, University of Washington. https://depts.washington.edu/nnmrec/docs/20101207_JavaherchiT_thesis_Turbine.pdf

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. http://meetings.aps.org/Meeting/DFD09/Event/112286

Javaherchi, T., A. Aliseda. (2010). Numerical Modeling of Hydrokinetic Turbines and their Environmental Effects *APS 63rd DFD Meeting*. Long Beach, CA. https://depts.washington.edu/nnmrec/docs/Javaherchi_APS_2010.pdf

Javaherchi, T., A. Aliseda. (2010). Numerical Modeling of Tidal Turbines: Near Wake Environmental Effects. *Eos Trans. AGU, 91(26),* Ocean Sci. Meet. Suppl. Abstract MT24A-08. Portland, OR. https://depts.washington.edu/nnmrec/docs/20100223_JavaherchiT_pres_AGU_NearWake.pdf

Javaherchi, T., J. Seydel, A. Aliseda. (2010). Numerical Modeling of Hydrokinetic Turbines and their Environmental Effects. *AGU Fall Meeting.* San Francisco, CA. Abstract OS11C-06. http://adsabs.harvard.edu/abs/2010AGUFMOS11C..06J


## Deliverable 2.2.2: An investigation of turbine depth on device performance in a sheared flow

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.

Hypothetical power dissipation by a tidal energy device was calculated for Admiralty Inlet, Washington, a highly energetic entrance channel to Puget Sound. Power dissipation was calculated as a function of hub height above sea bottom, using current profiler data taken in 2007 and 2009 at seven locations throughout the Inlet. At five of the locations, the tidal currents were predominantly bi- directional and power dissipation increased with height following a power law with the exponent ranging from 0.62 to 0.66, up to 18m. Where the water depth exceeded this substantially, power was found to increase further with height but at slower rates. At the remaining two sites the currents deviated significantly from bi- directionality, and power increased with exponents 0.35 – 0.5 and 0.91 – 0.96. The increase in power is faster than would be expected from the one-seventh power law applicable to open turbulent channels. However, it is still slower than the likely increase in the cost of device foundation with height, which would at a minimum be proportional to height due to the cost of materials alone. Thus, placing a tidal device high in the water column to exploit stronger currents may not be economically attractive, given that the device operator needs to recoup the higher cost of device foundation required.

### Related Publications

Kawase M., P. Beba, B. Fabien. (2011). Finding an Optimal Placement Depth for a Tidal In-Stream Conversion Device in an Energetic, Baroclinic Tidal Channel. *NNMREC Technical Report*. http://hdl.handle.net/1957/41897

## Deliverable 8.1.1: Simulations and parametric studies of field-deployed WEC devices. Support for design and development of a second generation WEC device.

Several studies on simulation and hardware comparison have been completed. The first is a paper on using AQWA and MATLAB models to predict performance of an autonomous wave energy converter compared to tank testing results. The second is a detailed analysis of WEC-Sim in predicting the performance of the Puget Sound deployed Columbia Power Technologies prototype in 2011. The findings have been that WEC-Sim does very well in predicting general behavior, including extremes in WEC motion, force, and power, which are important factors in initial design.

### Related Publications

Bosma B., T. Lewis, T. Brekken, A. von Jouanne. (2015). Wave tank testing and model validation of an autonomous wave energy converter. *Energies*. Vol. 8, pp. 8857–8872.

So R., C. Michelen, B. Bosma, P. Lenee-Bluhm, T.K. A. Brekken. Statistical Analysis of a 1:7 Scale Field Test Wave Energy Converter Using WEC-Sim. To be submitted to *IEEE Journal of Oceanic Engineering*.

## Deliverable 8.1.2: Complete fluid-structure interaction module and simulations of near-field wave scattering from a single WEC device with field data.

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 & b, 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 & b, and 2013) in the OSU field track. 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 of a current graduate student (J. Lou) in 2016.

### Related Publications

Elwood D., S.C. Yim, E. Amon, A. von Jouanne, T.K.A. Brekken. (2010a). Experimental Force Characterization and Numerical Modeling of a Taut-Moored Dual-Body Wave Energy Conversion System. *Offshore Mechanics and Arctic Engineering*, ASME. Vol.132, doi:10.1115/1.3160535.

Elwood D., S.C. Yim, E. Amon, A. von Jouanne, T.K.A. Brekken. (2011). Estimating the Energy Production Capacity of a Taut-Moored Dual-Body Wave Energy Conversion System Using Numerical Modeling and Physical Testing. *Offshore Mechanics and Arctic Engineering*, ASME. Vol.133, No.2, doi: 10.1115/1.4003184.

Elwood D., S.C. Yim, J. Prudell, C. Stillinger, A. Brown, A. von Jouanne. T. Brekken, R. Paasch. (2010b). Design, Construction, and Ocean Testing of a Taut-Moored Dual-Body Wave Energy Converter with a Linear Generator Power Take-Off. *Renewable Energy*. Vol.35, No.2, doi:10.1016/j.renene.2009.04.028, pp.348-354.

Lou J. PhD thesis (to be published).

Rhinefrank K., A. Schacher, J. Prudell, E. Hammagren, Z. Zhang, C. Stillinger, T.K.A. Brekken, A. von Jouanne, S.C. Yim. (2011). Development of a Novel 1:7 Scale Wave Energy Converter. *Offshore Mechanics and Arctic Engineering Conference*. Rotterdam, The Netherlands. Paper No. OMAE2011-50336.

Rhinefrank K., A. Schacher, J. Prudell, J. Cruz, N. Jorge, C. Stillinger, D. Naviaux, T. Brekken, A. von Jouanne, D. Newborn, S.C. Yim, D.T. Cox. (2013). Numerical Analysis and Scaled High Resolution Tank Testing of a Novel Wave Energy Converter. *Offshore Mechanics and Arctic Engineering*. ASME. Vol.135(4), 041901, doi: 10.1115/1.402886, pp.1-10.

Rhinefrank K., A. Schacher, J. Prudell, J. Cruz, N. Jorge, C. Stillinger, D. Naviaux, T.K.A. Brekken, A. von Jouanne, D. Newborn, S.C. Yim, D. Cox. (2010b). Numerical and Experimental Analysis of a Novel Wave Energy Converter. *Offshore Mechanics and Arctic Engineering Conference*. Shanghai, China. Paper No. OMAE2010-20901.

Rhinefrank K., A. Schacher, J. Prudell, C. Stillinger, D. Naviaux, T.K.A. Brekken, A. von Jouanne, D. Newborn, S.C. Yim, and D. Cox. (2010a). High Resolution Wave Tank Testing of Scaled Wave Energy Devices. *Offshore Mechanics and Arctic Engineering Conference*, Shanghai, China, Paper No. OMAE2010-20602.

## Deliverable 8.1.3: Initial simulations involving multiple devices using near shore wave model.

The SWAN model was calibrated for the NETS and SETS sites using existing AWAC data. Aaron Porter first performed initial simulations involving multiple devices using nearshore wave model (SWAN) configured for the Newport domain. This is documented in his thesis listed below.

### Related Publications

Porter, Aaron. (2012). Laboratory observations and numerical modeling of the effects of an array of wave energy converters. Master's thesis, Oregon State University. http://hdl.handle.net/1957/33928

Porter, A. K., M. C. Haller, P. Lenee-Bluhm. (2012). Laboratory observations and numerical modeling of the effects of an array of wave energy converters. *33rd International Conference on Coastal Engineering.* Santander, Spain. doi:10.9753/icce.v33.management.67.

## Deliverable 8.1.4: Assessment of level of interaction between devices and the nature of constructive/destructive effects as a function of separation scales and wave characteristics.

Ozkan-Haller and Haller and students McNatt, Porter, and O'Dea validated two popular models with very different formulations: the phase-resolving model WAMIT and the phase-averaged model SWAN against wave data from an extensive set of WEC array experiments (conducted in collaboration with Columbia Power Technologies, Inc).The wave field in the lee of the WEC arrays was mapped and the wave shadow was quantified for all sea states. In addition, the WEC power capture performance was measured independently via a motion-tracking system and compared to the observed wave energy deficit (the wave shadow). The observations are consistent with the standing wave patterns predicted by WAMIT. This pattern is related to wave scattering processes, and its presence increases the magnitude of the wave shadow in the lee of WECs. The pattern is less pronounced at longer periods where the WEC behaves like a wave-follower. For these situations, the wave shadow is primarily controlled by the WEC energy capture. Overall, WAMIT displays skill in predicting the wave field both offshore and in the lee of WECs. The SWAN model accounts for the frequency-dependent energy capture of the devices and performs well for cases when the wave shadow is primarily controlled by the WEC energy capture. For regular wave cases, the inclusion of wave diffraction processes is necessary. However, predictions with SWAN for random waves with frequency and directional spreads capture the general character of the wave shadow even without diffraction effects. Finally, we suggest that WECs designed as wave followers can extract the desired wave energy while also minimizing wave shadow effect and therefore leading to more efficient arrays with minimal environmental impact.

Also, a new threshold for nearshore hydrodynamic impact due to Wave Energy Converter (WEC) arrays was defined based on the change in the alongshore wave-driven radiation stress gradients in the lee of the array. A parametric study was conducted using SWAN 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 generated alongshore gradients exceeding the impact threshold on a uniform beach were identified. Lastly, the methodology was applied to the NETS and SETS sites to assess the applicability of the results to sites with real 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.

### Related Publications

Haller M.C. (2013). A review of studies on the nearshore impact of wave energy arrays: What have we learned and what is still needed? *AGU Fall Meeting*. San Francisco, CA. Abstract: OS13E-03

O'Dea A., M.C. Haller. (2013). Analysis of the impacts of Wave Energy Converter arrays on the nearshore wave climate in the Pacific Northwest. *AGU Fall Meeting*. San Francisco, CA. Abstract: OS13E-07.

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*.

## Deliverable 8.1.5: Incorporation of more sophisticated representation of WEC devices into area wave models using results from wave-structure interaction module.

This work has involved a nested approach whereby the wave-structure interaction code WAMIT was used to model the detailed of the wave-structure interaction. Results from this model at the lee of an array of WECs could then be used as input to an area wave model (in this case SWAN) to observe the further modification to the wave field due to local bathymetric effects. Results indicated that the higher-fidelity representation of WECs with WAMIT agreed well with a more efficient representation of the WECs utilizing the frequency-dependent relative capture width formulation for realistic random waves with a realistic frequency and directional spread. This formulation was later adopted into SWAN-SNL and has been used in a variety of studies exploring the far field effects of WEC arrays.

### Related Publications

Oskamp, J.A., H.T. Özkan-Haller. (2010). Wave Predictions at the site of a wave energy conversion array. 32$^{nd}$ *International Conference on Coastal Engineering*. Shanghai, China.

Özkan-Haller, H.T., Merrick C. Haller, J. Cameron McNatt, A. Porter, P. Lenee-Bluhm. (2016). Analyses of wave scattering and absorption produced by WEC-arrays: Physical and numerical experiments and an assessment of nearshore impacts. *In review*.

## Deliverable 8.1.6: Initial interconnection of mechanical/electrical modeling tools to hydrodynamic modeling tools for modeling a single WEC device.

Electrical and mechanical modeling was addressed in initial control and modeling work and culminated in WEC-Sim, which comprehensively includes electrical, mechanical, hydraulic, and hydrodynamic systems.

Brekken et al. (2012) presents a methodology for generating largescale ocean wave power time-series data for use in utility integration studies. The methodology involves the generation of a realization of wave time series based on observed wave spectra from ocean buoys coupled with a simple representation of WEC behavior (as a wave follower) and a rudimentary power-take-off model to arrive at power estimates at high temporal resolution.

The methodology by Brekken et al. (2012) was used by Oskamp and Ozkan-Haller (2012) who utilized a more sophisticated WEC-response computation and power-take-off formulation (using the wave-structure interaction code WAMIT) and later by Parkinson et al (2015) and Garcia-Castano (2015) to analyze issues related to grid integration.

### Related Publications

Brekken T.K.A, H.T. Özkan-Haller, A. Simmons. (2012). A methodology for large-scale ocean wave power time-series generation. *IEEE Journal of Oceanic Engineering, Special Issue on Ocean Energy*. 37(2), doi: 10.1109/JOE.2012.2187393

Garcia-Castano, (2015). Power Output Calculations for an array of point-absorber wave energy converters. Master's thesis, Oregon State University. http://hdl.handle.net/1957/56243

Oskamp, J. H.T. Özkan-Haller. (2012). Power Calculations for a Passively Tuned Point Absorber Wave Energy Converter on the Oregon Coast. *Renewable Energy*, 45. doi: 10.1016/j.renene.2012.02.004.

Parkinson S., K. Dragoon, G. Reikard, G. Garcia-Medina, H.T. Özkan-Haller, T. Brekken. (2015). Integrating ocean wave energy at large scales: A study of the US Pacific Northwest. *Renewable Energy*, 76, 551-559, doi: 10.1016/j.renene.2014.11.038.

## Deliverable 8.2.1: A numerical model of wakes and flow redirection.

We created computational models for the DOE RM1 and for a helical crossflow turbine based on an internal UW design that was built for experimental validation. Fluent was used 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 the helical crossflow turbine. 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. We 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 Cp 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 (of 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.

## Related Publications

Adamski S. (2013). Numerical modeling of the effects of a free surface on the operating characteristics of Marine Hydrokinetic Turbines. Master's thesis, University of Washington. http://hdl.handle.net/1773/23339

Hall T.J., A. Aliseda. (2011). Numerical simulation of a cross flow Marine Hydrokinetic turbine. *APS 64th DFD Meeting*. Baltimore, MD. USA. http://adsabs.harvard.edu/abs/2011APS..DFD.H9004H

Javaherchi T., A. Aliseda. (2012). Calibration of Discrete Random Walk (DRW) Model via G.I Taylor's Dispersion Theory. *APS 65th DFD Meeting*. San Diego, CA. http://adsabs.harvard.edu/abs/2012APS..DFD.F1099J

Javaherchi T., O. Thulin, A. Aliseda. (2011). Numerical Simulations of Marine Hydrokinetic (MHK) Turbines Using the Blade Element Momentum Theory. *APS 64th DFD Meeting*. Baltimore, MD. http://adsabs.harvard.edu/abs/2011APS.DFD.H9007J

Javaherchi T.A., N. Stelzenmuller, A. Aliseda. (2013). Experimental and Numerical Analysis of the DOE Reference Model 1 Horizontal Axis Hydrokinetic Turbine. *1st Marine Energy Technology Symposium*, GMREC-METS13, Washington, DC. https://depts.washington.edu/nnmrec/docs/Javaherchi_1stMETS_DOERM1_final.pdf

Stelzenmuller N. (2013). Marine Hydrokinetic Turbine Array Performance and Wake Characteristics. Master's thesis. University of Washington. http://hdl.handle.net/1773/25163

Stelzenmuller N., 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.

## Deliverable 8.2.2: Calibration of wake models by field and flume data.

Lab-scale turbines were designed, built, and tested for the DOE RM1 and a helical cross-flow turbine. Experiments were conducted on these two lab models 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.

The sliding mesh model produced excellent results for the crossflow turbine, including the wake evolution, except on the sections of the helical blades where the flow is close to separation. Dynamic stall kept the flow attached, and producing torque on parts of the blade rotation where the angle of attack would clearly lead to separation on a static airfoil. Once the blade section went over that small range of angles of attack, the separation was well predicted and the torque extraction was quite close to experiments.

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.

### Related Publications

Adamski S. (2013). Numerical modeling of the effects of a free surface on the operating characteristics of Marine Hydrokinetic Turbines. Master's thesis, University of Washington. http://hdl.handle.net/1773/23339

Hall T.J. (2012) Numerical Simulation of a Cross Flow Marine Hydrokinetic Turbine. Master's thesis, University of Washington. https://depts.washington.edu/nnmrec/docs/20120315_HallT_thesis_CrossFlow.pdf

Javaherchi T. (2014). Numerical investigation of Marine Hydrokinetic Turbines: methodology development for single turbine and small array simulation, and application to flume and full-scale reference models. PhD thesis, University of Washington. https://depts.washington.edu/nnmrec/docs/20140822_JavaherchiT_thesis_TurbineModeling.pdf

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. http://vtechworks.lib.vt.edu/handle/10919/49223

Polagye B., R. Cavagnaro, A. Niblick, T. Hall, J. Thomson, A. Aliseda. (2013). Cross-Flow Turbine Performance and Wake Characterization. *1st Marine Energy Technology Symposium*. Washington, DC. http://www.globalmarinerenewable.com/images/cross%20flow%20turbine%20performance%20and%20wake.pdf

Sale, D., A. Aliseda. (2013). Simulation of Marine Hydrokinetic Turbines in Unsteady Flow using Vortex Particle Method. *APS 66th DFD Meeting*. Pittsburgh, PA. http://adsabs.harvard.edu/abs/2013APS..DFDE13005S

Sale, D., A. Aliseda. (2014). Simulation of Hydrokinetic Turbines in Turbulent Flow using Vortex Particle Method. *2nd Marine Energy Technology Symposium*. Seattle, WA. https://depts.washington.edu/nnmrec/docs/Sale_2014_METS_paper_Final.pdf

Sale, D., A. Aliseda, M.R. Motley, Y. Li. (2013). Structural Optimization of Composite Blades for Wind and Hydrokinetic Turbines. *1st Marine Energy Technology Symposium*. Washington, DC. https://depts.washington.edu/nnmrec/docs/Sale_(2013)_GMREC.pdf

## Deliverable 8.2.3: Engineering rules for flow redirection in large arrays.

Array models were built in Fluent using the lessons learned from the single turbine simulations and flume experiments. A wide range of spacing arrangements including coaxial placement, staggered rows, diamond patterns, etc., were simulated and the performance of the different patterns analyzed for the optimal use of channel area. A surprising result from this analysis was that the relative efficiency, the ratio of power extracted by a turbine over the kinetic energy flux that is actually reaching the rotor disk, was constant for the simulations using the Blade Element Model. This means that a simulation including all rows of a turbine array is not necessary in this method. The power produced by turbines in row N+1 can be computed from the flow field simulated with just N rows of turbines. Thus, a recursive optimization algorithm was developed for an array of turbines that simply placed the turbines in each row based on the locations of maximum kinetic energy flux. This is, of course, an oversimplification of the influence of wake dynamics, including rotation, on the flow on turbines in the wake of other turbines, but if the BEM implementation is to be used, as it is in many design codes, then significant computational savings can be achieved with this algorithm, compared to computing each array configuration with all turbines to do the optimization.

## Related Publications

Javaherchi T., N. Stelzenmuller, J. Seydel, A. Aliseda. (2013). Numerical Modeling and Experimental Analysis of Scale Horizontal Axis Marine Hydrokinetic (MHK) Turbines. *APS 66th DFD Meeting*. Pittsburgh, PA. http://adsabs.harvard.edu/abs/2013APS..DFDE13004J

Javaherchi T., N. Stelzenmuller, J. Seydel, A. Aliseda. (2014). Numerical Simulations and Experimental Measurements of Scale-Model Horizontal Axis Hydrokinetic Turbines (HAHT) Arrays. *APS 67th DFD Meeting*. San Francisco, CA. http://adsabs.harvard.edu/abs/2014APS..DFDD24005J

Javaherchi T., N. Stelzenmuller, A. Aliseda. *(*2015). Experimental and Numerical Analysis of a Small Array of 45:1 Scale Horizontal Axis Hydrokinetic Turbines based on the DOE Reference Model 1. *3rd Marine Energy Technology Symposium.* Washington DC. https://depts.washington.edu/nnmrec/docs/Aliseda_METS_paper_2015.pdf

Sale, D., A. Aliseda. (2014). Simulation of Hydrokinetic Turbines in Turbulent Flow using Vortex Particle Method. *2nd Marine Energy Technology Symposium*. Seattle, WA. https://depts.washington.edu/nnmrec/docs/Sale_2014_METS_paper_Final.pdf

Sale, D., A. Aliseda. (2014). Study of Hydrokinetic Turbine Arrays with Large Eddy Simulation. *APS 67th DFD Meeting*. San Francisco, CA. http://adsabs.harvard.edu/abs/2014APS..DFDA24001S

Stelzenmuller, N., A. Aliseda (2013). Experimental characterization of marine hydrokinetic (MHK) turbine array performance. *APS 66th DFD Meeting*. Pittsburgh, PA. http://adsabs.harvard.edu/abs/2013APS..DFDA13005S

# Deliverable 14.1.1: Simulations and parametric studies of the physical WEC array deployed in the field.

This deliverable overlaps with 14.1.2, and array simulation work done by McNatt and Brekken/Simmons/Ozkan-Haller.

## Related Publications

Cameron McNatt thesis 2012; chapter "Analyses of wave scattering and absorption produced by WEC-arrays: Physical and numerical experiments and an assessment of nearshore impacts" in the forthcoming book *Renewable Ocean Energy – Resource Characterization, Practical Energy Harvest and Effects on Physical Systems*

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

## Deliverable 14.1.2: Design, development and optimization of a WEC device array model.

In addition to work in McNatt's master's thesis (McNatt 2012), array optimization has also been addressed in the Dehlsen Centipod MPC control development work. It has been found that simple multibody control models can be formulated and successfully utilized in control.

### Related Publications

McNatt C. (2012). Wave field patterns generated by wave energy converters. Master's thesis, Oregon State University. http://hdl.handle.net/1957/33939

Starrett M., R. So, T.K.A. Brekken. Model Predictive Control of the Centipod WEC. Journal paper under development.

## Deliverable 14.1.3: Finalize development of an optimized array of WEC devices based on field data analysis and numerical parametric studies.

Deliverable was superseded by a subsequent DOE project, the Advanced Laboratory and Field Arrays.

## Deliverable 14.1.4: Complete assembly of integrated modeling framework.

The modeling framework has been implemented in several areas, detailed in the following publications. The three major products are as follows: WEC-Sim, the power-system wave park power output code, and the Dehlsen code. The first two are public, but not the last.

### Related Publications

Bosma B., Z. Zhang, T.K.A. Brekken, T. Ozkan-Haller, C. McNatt, S. Yim. (2012). Wave energy converter modeling in the frequency domain: A design guide. *Energy Conversion Congress and Exposition (ECCE)*. pp. 2099–2106.

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.

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

Parkinson S., K. Dragoon, G. Reikard, G. Garcia-Medina, H.T. Ozkan-Haller, T.K.A. Brekken. (2015) Integrating ocean wave energy at large-scales: a study of the US Pacific Northwest. *Renewable Energy*, vol. 76, pp. 551–559.

Richter M., M. Magana, O. Sawodny, T.K.A. Brekken. (2014). Power optimisation of a point absorber wave energy converter by means of linear model predictive control. *IET Renewable Power Generation.* Vol. 8, pp. 203–215.

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. http://energy.sandia.gov/wp-content/gallery/uploads/130911c.pdf

Ruehl K., T. K. 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 (CITRES).* Waltham, MA. pp. 379 –386.

So R., A. Simmons, T.K.A. Brekken, K. Ruehl, C. Michelen. (2015). Development of pto-sim: A power performance module for the open-source wave energy converter code wec-sim. *ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE*). Vol. 9. St. John's, Newfoundland, Canada. http://energy.sandia.gov/wp-content/uploads/2014/06/SAND2015-2069C.pdf

So R., S. Casey, S. Kanner, A. Simmons, T. K. Brekken. (2015). PTO-sim: Development of a power take off modeling tool for ocean wave energy conversion. *Power Energy Society General Meeting, IEEE*. pp. 1–5. http://energy.sandia.gov/wp-content/uploads/2014/06/2015-IEEE-PES_PTO-Sim_Nak.pdf

Starrett M., R. So, T. K. Brekken, A. McCall. (2015). Development of a state space model for wave energy conversion systems. *Power Energy Society General Meeting, IEEE*. pp. 1–5.

Starrett M., R. So, T. K. Brekken, and A. McCall. (2015). Increasing power capture from multibody wave energy conversion systems using model predictive control. *IEEE Conference on Technologies for Sustainability (SusTech).* pp. 20–26.

## Deliverable 14.1.5: Explore feedbacks between hydrodynamics and power capture and device efficiency.

Oskamp and Ozkan-Haller (2012) explored the effects of passively tuning point absorber wave energy converters. They considered idealized non-resonating wave energy converters with one year of measured spectral wave conditions from the Oregon coast. The power calculation is performed in the frequency domain assuming a passive tuning system which is tuned at time scales ranging from hourly to annually. It is found that for the analyzed array characteristics, there is 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.

Brekken extensively developed WEC models for control, including the development of Model Predictive Control for a system of 1 DOF bodies. The results showed that significant improvements in energy capture were possible using MPC, up to three times as much energy conversion in some simulations compared with passive damping control approaches.

### Related Publications

Oskamp J., H.T. Özkan-Haller. (2012). Power Calculations for a Passively Tuned Point Absorber Wave Energy Converter on the Oregon Coast. *Renewable Energy*, 45. doi: 10.1016/j.renene.2012.02.004.

## Deliverable 14.1.6: Documentation, manual, tutorial, and example cases for the resulting modeling tool.

See 14.1.4, utility-scale power output code (available on OSU repository), and WEC-Sim: http://wec-sim.github.io/WEC-Sim/

## Deliverable 14.2.1: Conduct Doppler profiling measurements to characterize the wake from a full-scale turbine.

The previously described (10.2.2) wake measurements characterized the wake from the RivGen cross-flow turbine. The turbulence is elevated (maximum is 120%) relative to the 10% free stream level for 25 diameters downstream of the turbine. The mean velocity is reduced (minimum is 1 m/s) relative to the 2 m/s free stream level for 75 diameters downstream of the turbine. These results are described in Guerra and Thomson [2016].

### Related Publications

Guerra M., J. Thomson. (2016). ORPC RivGen wake characterization. *4th Marine Energy Technology Symposium. Washington, DC.*
https://depts.washington.edu/nnmrec/docs/mets2016_GuerraThomson.pdf

## Deliverable 14.2.2: Verify and validate numerical models for wake propagation using field and laboratory wake measurements in order to develop empirical device spacing rules.

Experiments with 3 lab-scale DOE RM1 turbines were conducted at the Bamfield flume. Coaxial and lateral offset arrays were studied for two different downstream spacing for the three "rows", 5D and 7D. The wake recovery after each row was measured from PIV measurements. The power of each turbine row was measured and a model to relate it to wake recovery was developed. It was determined that, not surprisingly, the power in downstream turbines increased with lateral offset, from 0 to 0.25D to 0.5 D. More shockingly, the power increased for the third turbine compared to the second one. This non-intuitive result was related to the wake recovery in a highly confined environment. The second row of turbines acted as a turbulence source that helped mix the high velocity flow redirected by the first turbine towards the flume walls back into the core of the flow, reenergizing the wake. Thus, the kinetic energy flux in front of the third row of turbines almost reached the free stream value, particularly for the 7D spacing case, and thus the third turbine produced almost as much power as the front turbine.

Numerical models were validated and verified against the single turbine results. The different turbine implementations were used to simulate the experimental setups were measurements of turbine power and velocity wake profiles were obtained. The actuator disk model and the propeller model did not satisfactorily predict the wake recovery observed in the experiments. The LES and the Blade Element Model were able to capture the wake recovery due to enhanced mixing by the array in the confined flume. Additionally, the high blockage ratio also induced changes in the flow through the rotor, making the maximum of power extraction creep up from the design value of 7.15 to an experimental value of 8 for the first row and 8.2-8.5 for the second and third turbines. The Blade Element Model captured this result and showed, by removing the flume walls in the simulations, that this was entirely a blockage effect. LES simulations for the full three turbine array were too computational expensive to span the full TSR range of the experiments, so only one TSR (7.15) was simulated for the different turbine spacings

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.

### Related Publications

Javaherchi T., N. Stelzenmuller, A. Aliseda. (2015). Experimental and Numerical Analysis of a Small Array of 45:1 Scale Horizontal Axis Hydrokinetic Turbines based on the DOE Reference Model 1. *3rd Marine Energy Technology Symposium*. Washington DC.
https://depts.washington.edu/nnmrec/docs/Aliseda_METS_paper_2015.pdf

Stelzenmuller N. (2013). Marine Hydrokinetic Turbine Array Performance and Wake Characteristics. Master's thesis, University of Washington.
https://depts.washington.edu/nnmrec/docs/20131209_StelzenmullerN_thesis_ArrayOptimization.pdf

## Deliverable 14.2.3: Assess the stability of tidal turbines with moorings using numerical simulations.

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).

### Related Publications

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.

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix C: Deliverables for Tasks: 3, 9, 15**

***Collaboration/Optimization with Marine Renewable and Other Renewable Energy Sources***

**DOE Award Number: DE-FG36-08GO18179-M001**

**Period Covered: 9/15/2008 – 3/14/2016**

**Delivered: June 30, 2016**

**Northwest National Marine Renewable Energy Center**

**Oregon State University**

**University of Washington**

## Deliverables



## Deliverable 3.1: A report documenting potentials for cross-fertilization between other renewables and hydrokinetic.

Several papers have been published on the interaction between wave energy and other renewable sources, particularly in how it affects utility reserve requirements. The findings have been that ocean wave energy mixes well with the variability characteristics other renewables. It has been found that ocean wave energy should be cheaper to integrate into the grid than other renewables.

### Related Publications

Halamay D. A., T.K.A. Brekken. (2012). Impact of demand response and wind generation on reserve requirements in the US Pacific Northwest. *IEEE Power and Energy Society General Meeting*. pp. 1–7.

Halamay D. A., T.K.A. Brekken. (2011). Monte Carlo analysis of the impacts of high renewable power penetration. *Energy Conversion Congress and Exposition (ECCE*). Phoenix, AZ. pp. 3059–3066.

Halamay D., T.K.A. Brekken. (2011). Factorial analysis for modeling large-scale grid integration of renewable energy sources. *Power Tech*. Trondheim, Norway. pp. 1–6.

Halamay D.A., T.K.A. Brekken, A. Simmons, S. McArthur. (2011). Reserve requirement impacts of large-scale integration of wind, solar, and ocean wave power generation. *IEEE Transactions on Sustainable Energy*. Vol. 2, no. 3, pp. 321–328.

Halamay D., S. McArthur, T.K.A. Brekken. (2010). A methodology for quantifying variability of renewable energy sources by reserve requirement calculation. *Energy Conversion Congress and Exposition (ECCE)*. Atlanta, GA. pp. 666–673.

Halamay D., T.K.A. Brekken, A. Simmons, S. McArthur. (2010). Reserve requirement impacts of large-scale integration of wind, solar, and ocean wave power generation. *IEEE Power and Energy Society General Meeting*. Minneapolis, MN. pp. 1–7.

Parkinson S., K. Dragoon, G. Reikard, G. Garcia-Medina, H. T. Ozkan-Haller, T.K.A. Brekken. (2015). Integrating ocean wave energy at large-scales: a study of the US Pacific Northwest. *Renewable Energy*. Vol. 76, pp. 551–559.

## Deliverable 9.1: A report documenting the potential of hybrid renewable systems to accelerate deployment and development of economies of scale.

No report was written. NREL effort refocused towards supporting the design of the Mobile Ocean Test Berth, leveraging NREL experience with energy device testing and marine data collection. MOTB design review feedback delivered through meetings and marked up MOTB documents.

### Related Publications

NREL (2010). MOTB Operations Considerations Discussion Guide. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

## Deliverable 15.1: Protocols, instrumentation and accreditation plans for WEC testing.

To support the establishment of open-water test facilities for marine and hydrokinetic technologies, NREL collaborated with NNMREC to create draft guidelines 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 which 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

In addition, NREL supplied NNMREC with standard NREL Cooperative Research and Development Agreements and Technical Services Agreements

## Related Publications

Driscoll F.R. (2013). Guidelines for Open-Water Testing of Wave Energy Converters. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

NREL. (2013). Example Open Water Testing Plan. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

NREL. (2013). Northwest National Marine Renewable Energy Center (NNMREC): Testing Accreditation Guidance. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

NREL. (2012). NNMREC Device Testing Notes: Agreements and Environmental, Health and Safety Planning. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix D: Deliverables for Tasks: 4, 10, 16**
***Integrated and Standardized Test Facility Development***

**DOE Award Number: DE-FG36-08GO18179-M001**
**Period Covered: 9/15/2008 – 3/14/2016**
**Delivered: June 30, 2016**

**Northwest National Marine Renewable Energy Center**

**Oregon State University**
**University of Washington**

## Deliverables



## Deliverable 4.1.1: Results of international ocean energy market survey.

An international ocean energy market survey was supported by the Close to the Customer (C2C) group in the Oregon State College of Business. This survey was partially supported by the Oregon Wave Energy Trust (OWET). The results of this survey were used to support early planning for NNMREC's ocean testing programs.

## Related Publications

Close to the Customer. (2009). Final report presentation to NNMREC and OWET. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

Close to the Customer. (2009). NNMREC Close to the Customer Survey, Summary Report and Recommended Strategies. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

## Deliverable 4.1.2: Design of full scale mobile PADA test berth.

For the design of a full scale (500 kW – 1 MW) mobile power analysis and data acquisition (PADA) test berth for the testing of wave energy converters (WECs), OSU went through an open RFP process and selected an industry team led by Science Applications International Corporation (SAIC), with subcontractors including Hyak Electroworks, Peregrine Power, Renewable Energy Composite Solutions (RECS), and Glosten Associates. The team of SAIC and subcontractors worked with OSU, NNMREC, and WEC developers to complete the specifications and preliminary design of the Mobile Ocean Test Berth (MOTB). The preliminary design of the full scale MOTB commenced January 14th, 2010, and concluded with the preliminary design review meeting held at OSU on June 9th, 2010. Through the preliminary design process, two significant design challenges emerged rendering the *full scale* system unfeasible at that time, namely grid mimic capabilities as well as the submarine power cable and the interconnection to the MOTB and the wave energy converter (WEC) under test.

NNMREC then assembled a group of outside experts to review alternatives and provide expert feedback to consider in planning the path forward. The external review panel included: NREL, Cardinal Engineering (DOE contractor), Fishermen, Columbia Power Technologies and L-3 MariPro. Through these discussions NNMREC was recommended to pursue a phased test facility process toward a cable-to-shore based test berth that can test multiple devices:

PHASE 1: Permitted Open-Ocean Test Site

- Phase 1a: Develop Permitted Open-Ocean Test Site
- Phase 1b: Develop Testing Protocols for Open Ocean Testing
- Phase 1c: Build 30 – 100 kW Testing Platforms for scaled testing
- Phase 2: Utility Scale, Grid-connected Wave Energy Test Site
- Up to four 4 separate cables, 5-8 miles from shore for testing individual WECs or arrays
- Grid Emulator for non grid-connect testing

Through this phased process NNMREC branded our marine energy converter testing facilities as the Pacific Marine Energy Center (PMEC), including scaled lab testing facilities, intermediate and full-scale open water testing facilities. Phase 1 developed into the PMEC-NETS (North Energy Test Site), including the 100kW Ocean Sentinel MOTB testing platform. Phase 2 developed into the PMEC-SETS (South Energy Test Site).

For the Phase 1 MOTB 100 kW testing platform NNMREC spring-boarded off of the full scale design, and worked with AXYS Technologies on the development of the Ocean Sentinel instrumentation buoy. The Ocean Sentinel is a surface buoy, based on the 6-meter NOMAD (Navy Oceanographic Meteorological Automatic Device) buoy design. The Ocean Sentinel facilitates open-ocean, stand-alone testing of WECs with average power outputs of up to 100 kW, and provides power analysis and data acquisition, environmental monitoring, as well as an active converter interface to control power dissipation to an on-board electrical load. The WEC being tested and the Ocean Sentinel instrumentation buoy are moored with approximately 125 meters separation; connected by a power and communication umbilical cable. The Ocean Sentinel was completed in 2012, and was deployed for the testing of a WEC at the PMEC-NETS, north of Newport, OR, during August and September of 2012.

### Related Publications

von Jouanne A., T. Lettenmaier, E. Amon, T. Brekken, R. Phillips. (2013). A Novel Ocean Sentinel Instrumentation Buoy for Wave Energy Testing. *Marine Technology Society (MTS) Journal*.

SAIC. (2010). Concept of Operations – Mobile Ocean Test Berth. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

## Deliverable 4.1.3: Initial ship-board deployment of radar wave imaging system for site characterization.

Original project plans included collecting remote sensing observations of devices under ocean testing. However, since only single devices were deployed at Newport NETS, and only during mild summer conditions, there was not a good opportunity for this type of data collection. Hence, site characterization was conducted with in situ measurements. In terms of wave characterization, early in the project before wave monitoring of the test sites had a chance to get off the ground, a numerical wave model (SWAN) was used to transform the offshore wave climatology (i.e. NDBC Station 46050) to NETS. Examples of the transformed monthly climatologies are given below.

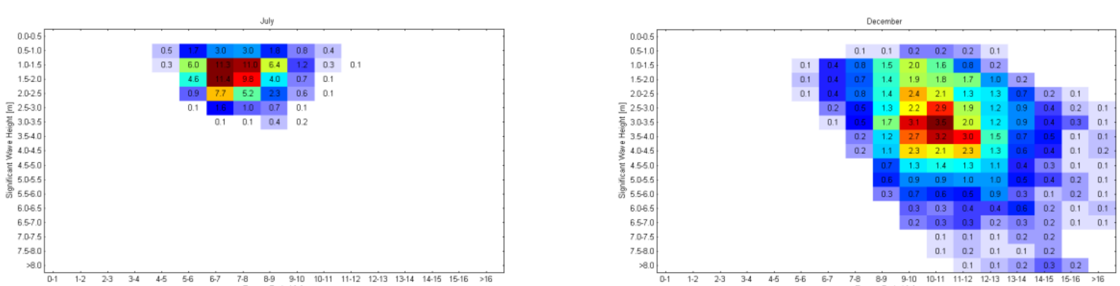



Figure 1: Average monthly wave climatologies at NETS determined from wave model transformation of the NDBC 46050 buoy records; (left) July and (right) December.

## Deliverable 4.2.1: Trialing of stand-alone packages for over-the-side and bottom mounted monitoring.

From April 2009 to Oct 2013, a total of 16 over-the-side surveys and 27 bottom-mount deployments were conducted at the Admiralty Inlet tidal energy site. Both approaches were continually refined over time. Central to the trials were the operational constraints of working in strong tidal currents (up to 8 knots). Both the over-the-side and bottom-mounted approaches were proven to be successful in using Acoustic Doppler Current Profilers to characterize the tide currents. The final over-the-side method was achieved by repeated station keeping. The final bottom-mount method was achieved using reinforced fiberglass "sea spider" tripods with 800 lbs lead ballast, deployed and recovered via acoustic releases. The results and recommendations, along with the data, were published online at http://depts.washington.edu/nnmrec/project_meas.html#admiralty

## Deliverable 4.2.2: Published guidelines for best practices in instrumentation and monitoring.

These were published in several journal publications. Palodichuk (2013) presented and validated a method for conducting over-the-side surveys of tidal currents by sequentially holding stations on a repeating circuit throughout a tidal cycle, building on the methodology developed by Epler (2011). Polagye and Thomson (2013) presented and demonstrated methods for bottom-mounted sampling of tidal currents, including error estimation based on finite record lengths and spatial variability, building on initial work by Gooch (2009). Bassett et al (2013) and Bassett et al (2014) demonstrated the importance of bedload sediment transport and turbulence, respectively, in passive acoustic monitoring.

### Related Publications

Bassett C., J. Thomson, P. Dahl, B. Polagye. (2014). Flow noise and turbulence in two tidal channels. *Journal of the Acoustical Society of America.* 135.

Bassett C., J. Thomson, B. Polagye. (2013). Sediment-generated noise and bed stress in a tidal channel. *Journal of Geophysical Research.* 118.

Epler, J., B. Polagye, B., J. Thomson. (2010). Shipboard acoustic Doppler current profiler surveys to assess tidal current resources. *MTS/IEEE Oceans 2010*. Seattle, WA. 10 pp. http://depts.washington.edu/nnmrec/docs/20100920_EplerJ_conf_MobileADCP.pdf

Gooch, S., J. Thomson, B. Polagye, D. Meggitt. (2009). Site characterization for tidal power. *MTS/IEEE Oceans 2009*. Biloxi, MS. 10 pp. http://depts.washington.edu/nnmrec/docs/20090820_GoochS_conf_SiteCharacterization.pdf

Palodichuk M., B. Polagye, J. Thomson. (2013). Resource mapping at tidal energy sites*. Journal of Oceanic Engineering.* 38.

Polagye B., J. Thomson. (2013). Tidal energy resource characterization: methodology and field study in Admiralty Inlet, Puget Sound, US. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*. 227.

## Deliverable 10.1.1: Construction and deployment of full-scale mobile PADA test berth. Results from wave monitors and WEC devices placed at the Center demonstration site.

As discussed in "4.1.2 Design of full scale mobile PADA test berth", construction of a "full scale" mobile PADA was determined to be unfeasible at that time and thus NNMREC moved forward with the design and construction of a 100 kW Ocean Sentinel MOTB for testing WECs. The Ocean Sentinel is a surface buoy based on the 6-meter NOMAD (Navy Oceanographic Meteorological Automatic Device) design, where the 6m NOMAD supplier on the west coast is AXYS Technologies located in Sidney, British Columbia, Canada. The Ocean Sentinel provides power analysis and data acquisition, environmental monitoring, as well as an active converter interface to control power dissipation to an on-board electrical load. The instrumentation buoy facilitates open-ocean, stand-alone testing of WECs with average power outputs of up to 100 kW. The wave energy converter (WEC) under test and the instrumentation buoy will be moored with approximately 120 meters separation, connected by a power and communication umbilical cable. The requirements and specifications for the umbilical cable were developed, as well as for the telemetry system, switchgear, converter and load bank to ensure integration readiness for deployment in the summer of 2012.

The design and construction of the Ocean Sentinel buoy was completed with AXYS Technologies in the spring of 2012, and the NOMAD hull was delivered to the Toledo Boatyard on July 25th, 2012. Upon arrival of the Ocean Sentinel, training and commissioning commenced, including re-assembly of equipment (such as masts and instrumentation) that needed to be removed for shipping. Our NNMREC team also began the integration of the switch gear, converter, load banks and telemetry system, as well as the mounting structures for the umbilical cable. Two umbilical cable systems were procured, namely a lower power cable (20 kW) for testing lower power (scaled) devices, and a full capacity cable (100 kW). The lower power cable was used for this summer 2012 testing of the WET-NZ device. The WET-NZ device arrived at the Toledo Boatyard the week of August 6th, which was followed by system integration (e.g., of the power pod) and commissioning of the systems including collaborations with NREL and the integration of their instrumentation modules.

The Ocean Sentinel anchors/moorings were deployed the week of August 13th, along with the NNMREC Test Site corner marker buoys, all at the PMEC-NETS. On August 17th, the Ocean Sentinel was towed from the Toledo Boatyard to the Newport Ship Ops (it was docked at the pier near the Hatfield Marine Science Center). On August 19th, the Ocean Sentinel was deployed using the OSU Pacific Storm, along with the TRIAXYS wave monitoring buoy used for measuring wave magnitude, period, direction, and currents. Results from the TRIAXYS wave monitoring buoy and the WEC testing at the PMEC-NETS demonstration site are also included in the deployment publication below.

On August 20th the WET-NZ was towed from the Toledo Boatyard to Newport, and the anchors/moorings were deployed that August 20th and 21st. The WET-NZ device itself was deployed on August 22nd, along with the umbilical cable. The umbilical cable was also connected from the WET-NZ to the Ocean Sentinel on August 22nd.

The WET-NZ was tested using the Ocean Sentinel 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. The Ocean Sentinel and umbilical cable were removed on October 5th, followed by decommissioning activities, and the WET-NZ was removed on Oct. 6th, with all remaining anchors/moorings removed using the NRC Quest.

Note that with the three-point moor used with the Ocean Sentinel/NOMAD hull (to prevent twisting of the umbilical cable) the testing window for wave energy testing is May – October. If no umbilical cable is connected, the Ocean Sentinel/NOMAD can be moored using a single-point moor, which can be deployed all months of the year, e.g., for environmental testing etc.

NNMREC continued to work closely with the US Coast Guard to ensure that the test site was appropriately marked, e.g., using marker buoys with specified navigation lighting and flash sequences as well as reflectors.

### Related Publications

Lettenmaier T., A. von Jouanne, E. Amon, S. Moran, A. Gardiner. (2013). Testing the WET-NZ Wave Energy Converter using the Ocean Sentinel Instrumentation Buoy. *Marine Technology Society (MTS) Journal*.

## Deliverable 10.1.2: Radar deployments and analysis of radar/AWAC/Waverider observations.

Radar deployments are discussed in 4.1.3 and 16.1.1. AWAC & Waverider observations and analysis are covered in 16.1.1, 16.1.3, and 16.1.4.

## Deliverable 10.1.3: Design and bid process for multiple full-scale test berths.

Before the NNMREC team started work on this deliverable, the team realized that the developer desire was for a grid-connected test facility rather than multiple Ocean Sentinels. Hence, this deliverable was not completed.

## Deliverable 10.2.1: Free-stream turbulence measurements and a correlation of turbulence with device performance.

Free stream turbulence measurements were made upstream of the ORPC "RivGen" in Alaska turbine during the summers of 2014 and 2015. A total of over 100 hours of data were collected with device performance simultaneously measured. The preliminary correlation of turbulence and performance was inconclusive, however, because the turbulence did not vary significant at this site (10% constant turbulence intensity). Further analysis is ongoing.

Additional free stream turbulence measurements were made at the Admiralty Inlet site, however a turbine was not in place for performance correlation (due of the cancelation of the Snohomish PUD project intending to use Open Hydro turbines). The turbulence data have been posted here:

http://faculty.washington.edu/jmt3rd/TidalTurbulenceData/

### Related Publications

Thomson J., B. Polagye, M. Richmond, V. Durgesh. (2010). Quantifying turbulence for tidal power applications. *MTS/IEEE Oceans 2010*. Seattle, WA.
http://depts.washington.edu/nnmrec/docs/20100920_ThomsonJ_conf_Turbulence.pdf

Thomson J., B. Polagye, V. Durgesh, M. Richmond. (2012). Measurements of turbulence at two tidal energy sites in Puget Sound, WA (USA). *IEEE Journal of Oceanic Engineering.* 37(3)
http://depts.washington.edu/nnmrec/docs/Thomson%20et%20al.%20(2012)%20-%20Turbulence.pdf

## Deliverable 10.2.2: Wake measurements.

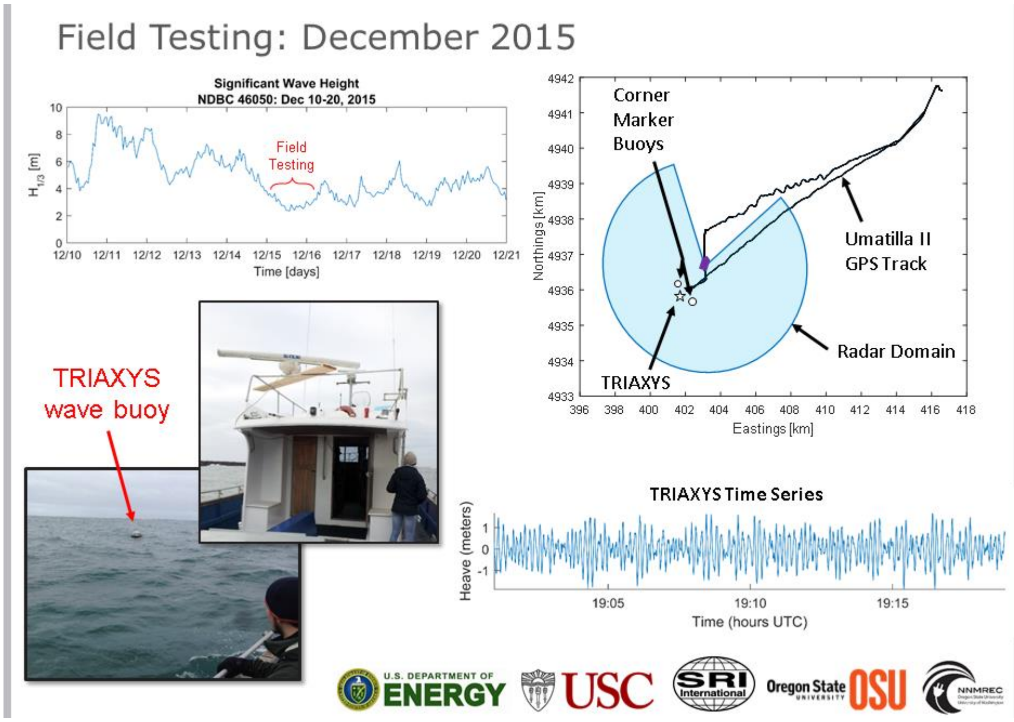
Wake measurements from the OPRC RivGen turbine were made as part of the same field effort to collect free stream turbulence data in the summers of 2014 and 2015. The 2015 dataset is the most complete, with over 300 streamwise measurements with a Doppler profiler looking down from a new prototype of the pre-existing Surface Wave Instrument Float with Tracking (SWIFT). These measurements have been gridded, using onboard GPS, into a data product with 2 x 2 m spatial resolution in the horizontal and 0.5 m resolution in the vertical. The measurements extend up to 300 m downstream of the turbine (150 diameters). The time resolution is 8 Hz.

### Related Publications

Guerra Paris M., J. Thomson. (2016). ORPC RivGen wake characterization. *4th Marine Energy Technology Symposium*. Washington, DC.
http://depts.washington.edu/nnmrec/docs/mets2016_GuerraThomson.pdf

## Deliverable 16.1.1: Routine radar and in-situ deployments and analysis, support for model validation

Late in the project, radar observations were collected at the Newport SETS site during a deployment of the TRIAXYS buoy. This work was leveraged with a separate DOE funded project. The figure below illustrates the shipboard radar data collection exercise at SETS. Data was collected synchronously and co-located with the TRIAXYS wave buoy. See Deliverables 16.1.3 and 16.1.4 for discussion of the TRIAXYS data.




## Related Publications

Simpson A., M.C. Haller, D. Walker, P. Lynett, R. Pittman, and D. Honegger. (2016). Assimilation of wave imaging radar observations for real-time wave-by-wave forecasting, Published abstract and poster presentation. *AGU Ocean Sciences Meeting*. New Orleans, LA.

Simpson, A., M.C. Haller, D. Walker, P. Lynett, and R. Pittman. (2016). Real-time wave-by-wave forecasting via assimilation of marine radar data. Extended abstract and oral presentation. *4th Marine Energy Technology Symposium*. Washington, DC, http://events.pennwell.com/nha2016/Custom/Handout/Speaker70216_Session15746_1.pdf.

## Deliverable 16.1.2: Planning documents for design of multiple cable-to-shore test berths and related on-shore infrastructure.

The plans for a grid connected test facility for multiple cable to shore berths for wave energy converters began with a feasibility study that Pacific Energy Ventures (PEV) performed for NNMREC with support from Parametrix. While the non-grid connected test facility where Ocean Sentinel is deployed (which has come to be known as the Pacific Marine Energy Center North Energy Test Site, PMEC-NETS) could conceivably be the site of the grid connected facility (now known as PMEC-South Energy Test Site, PMEC-SETS), the feasibility study from PEV sought to answer to questions:

- Identify the site characteristics required for the successful development of PMEC-SETS
- Conduct a technical evaluation of candidate sites that meet these criteria.

PEV provided this study to NNMREC in December 2011 and four potential sites for PMEC-SETS were identified: Camp Rilea in Warrenton OR; Newport, OR; Reedsport, OR; and Coos Bay OR. Before further planning documents could be developed, NNMREC was awarded $4 million to develop PMEC-SETS. The planning work was then shifted to Tasks 19 through 22 of this grant.

### Related Publications

Pacific Energy Ventures. (2011). Feasibility Study for a Grid Connected Pacific Marine Energy Center. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

## Deliverable 16.1.3: Results from wave monitors and WEC devices placed at the NW National Marine Energy Center demonstration site.

## Deliverable 16.1.4: Results of wave observation analysis.

Results from the TRIAXYS wave monitoring buoy along with the WEC testing at the PMEC-NETS demonstration site in the summer of 2012 are included in the deployment publication below.

NNMREC has also been collecting data from wave monitors from the PMEC-SETS, through the end of Dec. 2015, where these latest results are pending publication. TRIAXYS data for two deployment months (November 9th 2014 to January 23rd 2015) is shown in Figure 1 as a percentage occurrence matrix. The most common conditions are wave periods of approximately 10 seconds and wave heights of approximately 2 meters. Figure 2 shows the time-series of significant wave heights (averaged over 20 minute intervals) for November 9th 2014 to January 23rd 2015. In Figure 2, 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 1: Occurrence Matrix for November 9th 2014 to January 23rd 2015 at PMEC-SETS. Matrix entries are percentage of time.**

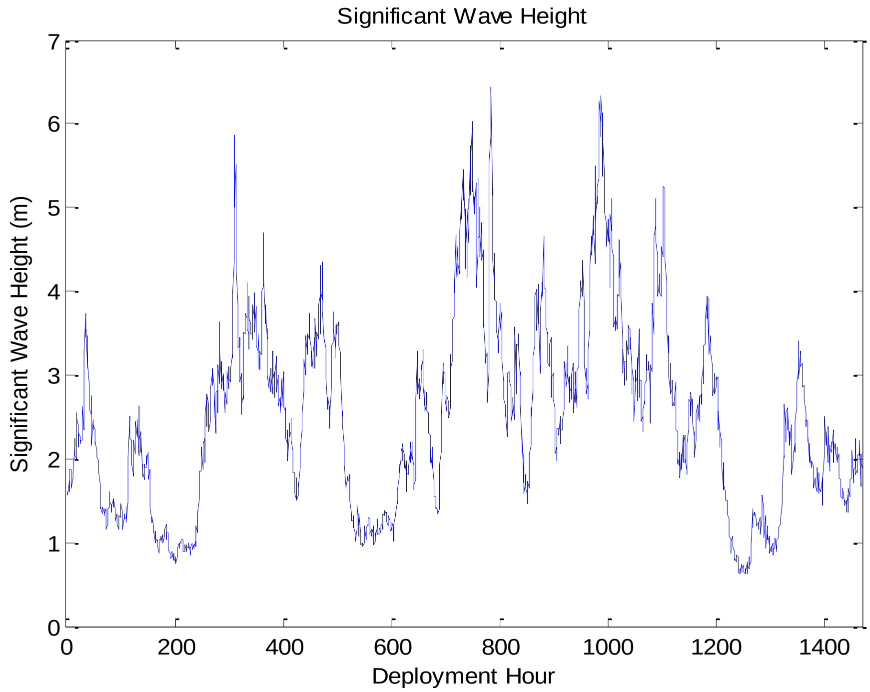



**Figure 2: Significant Wave Heights for November 9th 2014 to January 23rd 2015at PMEC-SETS.**

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

The TRIAXYS was redeployed at PMEC-SETS in May 2015 where Figure 3 shows the Probability Density Function (PDF) of the significant wave height for May 25$^{th}$ 2015 to December 29$^{th}$ 2015. The PDF graphs show the significant wave heights that are the most likely to occur during those months. Figure 4 displays the PDF for wave period for May 25$^{th}$ 2015 to December 29$^{th}$ 2015. Figures 5 and 6 show the significant wave heights and periods (averaged over 20 minute intervals) for the same deployment period of May 25$^{th}$ 2015 to December 29$^{th}$ 2015. Several peaks are evident in the two plots, which correlate to stormier weather.

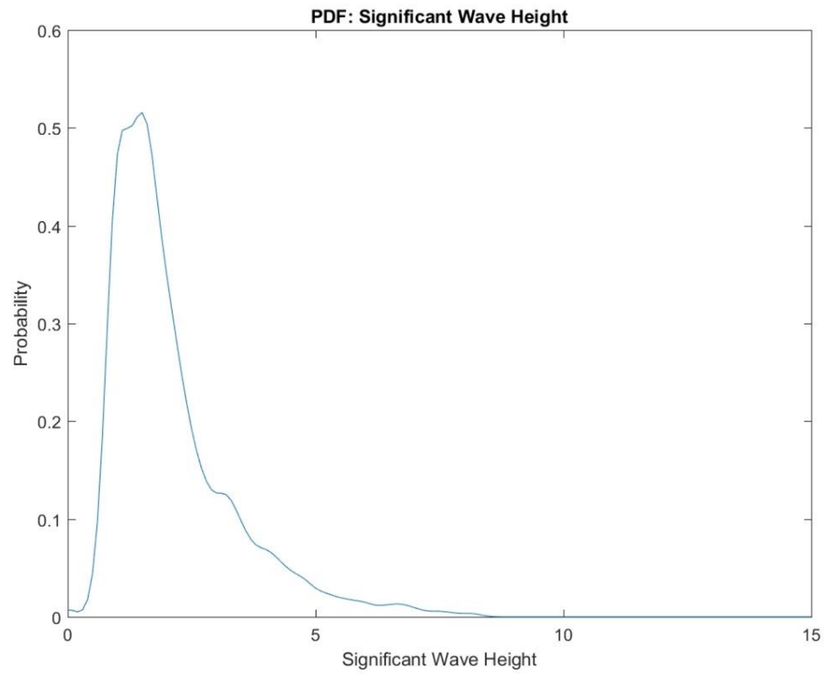



**Figure 3: Probability Density Function of significant wave height for May 25th 2015 to December 29th 2015 at PMEC-SETS.**

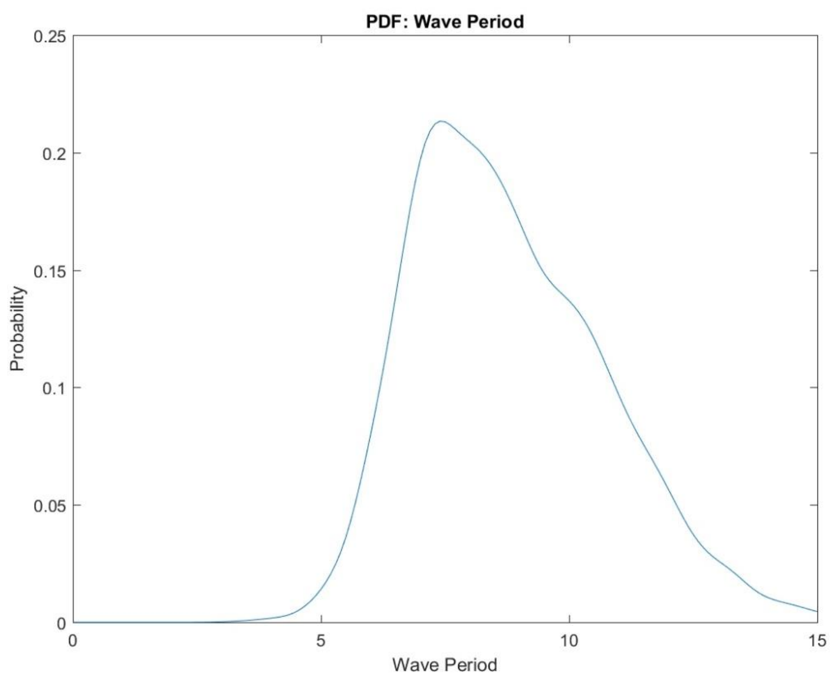



**Figure 4: Probability Density Function of wave period for May 25th 2015 to December 29th 2015 at PMEC-SETS.**

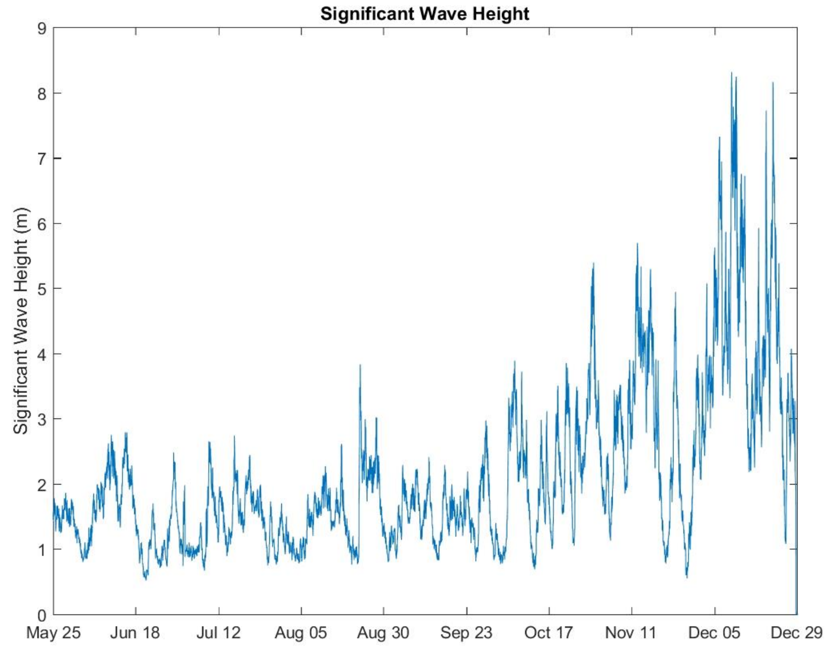



**Figure 5: Significant Wave Heights for May 25th 2015 to December 29th 2015at PMEC-SETS.**

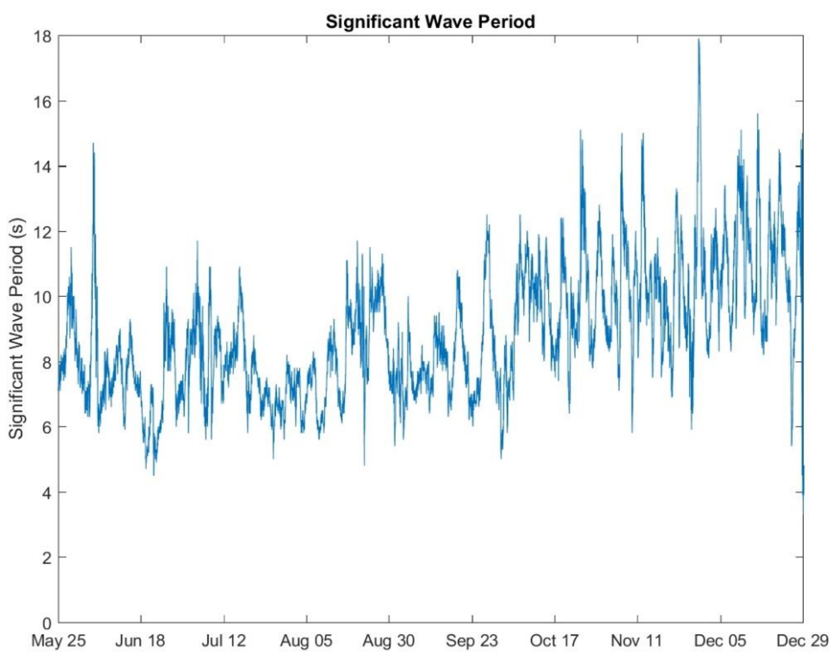



**Figure 6: Significant Wave Periods for May 25th 2015 to December 29th 2015 at PMEC-SETS.**

### Related Publications

Lettenmaier T., A. von Jouanne, E. Amon, S. Moran, A. Gardiner. (2013). Testing the WET-NZ Wave Energy Converter using the Ocean Sentinel Instrumentation Buoy. *Marine Technology Society (MTS) Journal*.

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*. Washington DC. *http://www.nationalhydroconference.com/index/post-show/2015-mets-presentations.html*

## Deliverable 16.2.1: Report describing options for cost-effective monitoring of commercial arrays.

Cost-effective environmental monitoring for commercial arrays of tidal turbines is predicated on retiring risk at the pilot scale. In general terms, two types of risk are most difficult to retire: those associated with rare, but potentially significant, interactions (e.g., collision leading to mortality) and those that occur commonly, with an indeterminate ultimate effect (e.g., exposure to turbine sound). Intensive monitoring for rare events is unlikely to be cost-effective for arrays consisting of more than a few turbines, given the high-cost nature of integrated instrumentation packages to classify interactions without incurring a data mortgage. However, common, low-level effects (e.g., avoidance behavior) may only be observable at the commercial-scale. Cost-effective monitoring of these effects to retire risk will require a mix of fixed and distributed instrumentation systems, leveraging the lessons learned from pilot scale monitoring. Capabilities and gaps for pilot- and commercial-scale environmental monitoring of marine energy converters are comprehensively described in a report from a DOE-supported workshop. 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.

### Related Publications

Polagye B., A. Copping, R. Suryan, S. Kramer, J. Brown-Saracino, C. Smith. (2014). Instrumentation for monitoring around marine renewable energy converters: Workshop final report, PNNL-23110, Pacific Northwest National Laboratory, Seattle, WA.

## Deliverable 16.2.2: Continue field data collection from Admiralty Inlet until June 2013 to obtain four years of uninterrupted baseline data describing tidal currents, underwater noise, and marine mammal presence/absence.

Baseline data collection continued uninterrupted for over four years at the Admiralty Inlet tidal energy site. Data collection supported the FERC application of the Snohomish PUD and the planning for the installation of two OpenHydro turbines (later cancelled). The data enabled development of the best-practices method for resource characterization reported in Polagye & Thomson (2013), including a published software toolbox available at:

http://depts.washington.edu/nnmrec/project_meas.html#char

Data are available at: http://depts.washington.edu/nnmrec/project_meas.html#admiralty

### Related Publications

Polagye B., J. Thomson. (2013). Tidal energy resource characterization: methodology and field study in Admiralty Inlet, Puget Sound, US. *Institution of Mechanical Engineers, Part A: Journal of Power and Energy*. 227.

## Deliverable 16.2.3: Develop protocols to quantify design velocities at tidal energy sites from current measurements and meteorological data (deterministic tidal currents, turbulence, estuarine circulation, storm surges, etc.).

Design loads on tidal turbines vary approximately with the square of current velocity. For fixed-pitch turbines, peak loads correspond with peak currents, while variable-pitch turbine blades experience peak loads closer to rated velocity. This work focused on the former, since the methods are readily extended to the latter. The design velocity can be considered as the sum of deterministic (i.e., periodic) currents and meteorological currents (e.g., storm surge), multiplied by a factor accounting for turbulence. Wave orbital velocities can be included within the framework but are not explicitly treated given the limited wave action in Admiralty Inlet, where data collection underpinned the analysis.

Analysis of multi-year current measurements in Admiralty Inlet show that the peak observed mean currents corresponded to a ~1.2 multiplier on the peak currents predicted by harmonic analysis. Storm surges would be likely to contribute, at most a 0.5 m/s increase at the site, based on a regression of measured peak currents to tidal range and historic information about maximum storm surges in Puget Sound. Because a historically large storm surge would be unlikely to coincide with the perigean spring currents, the contribution of storms to design velocities was discounted by a factor of 0.2 (chosen semi-arbitrarily). Analysis of shorter-duration turbulence data collected from Admiralty Inlet suggests that, during periods of peak currents, instantaneous currents are likely to be no more than 1.2 times greater than the mean (99.9$^{th}$ percentile currents). In combination, these suggest that ~65% of design loads may be attributed to periodic currents, ~3% to storm surges, and ~32% to turbulence. Results are site specific, but suggest that the greatest benefits for reduced uncertainty in load characterization lie with an improved understanding of turbulent extrema and multi-year observations of mean currents.

## Related Publications

Polagye B. (2014). Design load estimation for tidal turbines from a multi-year measurement time series. Presentation and abstract. *International Conference on Ocean Energy*. Halifax, Nova Scotia. https://depts.washington.edu/nnmrec/docs/20141106_PolagyeB_pres_DesignLoad.pdf

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix E: Deliverables for Tasks: 5, 11, 17**
***Investigate the Compatibility of Marine Technologies with Environment, Fisheries and other Marine Resources***

**DOE Award Number: DE-FG36-08GO18179-M001**
**Period Covered: 9/15/2008 – 3/14/2016**
**Delivered: June 30, 2016**

**Northwest National Marine Renewable Energy Center**

**Oregon State University**
**University of Washington**

## Deliverables



## Deliverable 5.1: Initial environmental site characterization work for Center demonstration facility. Initiate marine mammal behavioral research around wave energy facilities.

### Environmental Characterization Work

The goal of this project was baseline characterization via observations and sample collection of the habitat and biological assemblages present at the future site of the Northwest National Marine Renewable Energy Center (NNMREC) Ocean Test Facility (now referred to as the North Energy Test Site) near Newport, OR. Specifically, CTD casts, box core and beam trawl collections, and video observations were conducted at the site from spring 2010 to fall 2011. These collections and observations help characterize the baseline variability in habitat and species characteristics across seasons over two years. Below we summarize overall findings. In the following document we report on the spatial and temporal variability of the habitat features and biological assemblages. Finally, we review our participation to date in disseminating these results and outline plans for post-installation monitoring of the Ocean Test Facility site.

### Marine Mammal Research

This study was conducted to determine whether a low-powered sound source could be effective at deterring gray whales from areas that may prove harmful to them. With increased interest in the development of marine renewal energy along the Oregon coast the concern that such development may pose a collision or entanglement risk for gray whales. A successful acoustic deterrent could act as a mitigation tool to prevent harm to whales from such risks. In this study, an acoustic device was moored on the seafloor in the pathway of migrating gray whales off Yaquina Head on the central Oregon coast. Shore-based observers tracked whales with a theodolite (surveyor's tool) to accurately locate whales as they passed the headland. Individual locations of different whales/whale groups as well as tracklines of the same whale/whale groups were obtained and compared between times with the acoustic device was transmitting and when it was off.

A successful deterrent device may serve as a valuable mitigation tool to protect gray whales, and other baleen whales, in the event that marine energy development poses a collision or entanglement risk.

## Related Publications

Henkel S. (2011). Baseline Characterization of Benthic Habitats and Organisms-Newport. Report published. http://hdl.handle.net/1957/29314

Lagerquist B., M. Winsor, B. Mate (2012). Testing the effectiveness of an acoustic deterrent for grey whales along the Oregon coast. Final Scientific Report for DOE. http://hdl.handle.net/1957/57536

## Deliverable 5.2: Utilize area wave model to transform wave field affected by a WEC device towards shore.

A nested Simulating WAves Nearshore (SWAN) model was used to analyze wave transformation and propagation in the lee of a large-scale WEC array at both the NNMREC North Energy Test Site (NETS) and the South Energy Test Site (SETS). The input directional wave spectra for the NETS and SETS simulations were obtained from a 2005-2011 coupled WAVEWATCH III and SWAN hindcast for the Pacific Northwest (García-Medina et al., 2013). The SWAN model was validated using existing data from an Acoustic Wave and Current Meter (AWAC) previously deployed within the model domain (Vardaro et al., 2011). WEC devices were represented in SWAN through the external modification of the wave spectra at the device location using an experimentally-determined Power Transfer Function (PTF) (Rhinefrank et al, 2013).

The nearshore wave model SWAN was used in this study. WAVEWATCH III model outputs were used as input conditions. This work was completed between April 2013 and September 2014.

### Related Publications

O'Dea A, M.C. Haller. (2014). Analysis of the Impacts of Wave Energy Converter Arrays on the Nearshore Wave Climate. *2nd Marine Energy Technology Symposium*. Seattle, WA. http://vtechworks.lib.vt.edu/bitstream/handle/10919/49231/112-ODea.pdf?sequence=1&isAllowed=y

O'Dea A. (2014). *On the Nearshore Impact of Wave Energy Converter Arrays*. Master's thesis, Oregon State University. http://hdl.handle.net/1957/52599

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.*

## Deliverable 11.1: Website and electronic document repository for environmental information.

This deliverable was made superfluous by the development of TETHYS at Pacific Northwest National Labs (PNNL), and was mutually decided with DOE to remove as a deliverable on this project. TETHYS can be found at http://tethys.pnnl.gov/.

## Deliverable 11.2: Initial acoustic assessment of existing wave energy facilities. Advise industry, agencies and other stakeholders on environmental effects (continuing activity).

On September 26th, 2013 passive acoustic recordings were made with a drifting hydrophone near NNMREC's Ocean Sentinel at the North Energy Test Site (NETS) off the central Oregon coast. The deployment of the Ocean Sentinel and facility marker buoys, in the absence of an operational wave energy converter (WEC) device, provided an opportunity to measure effects on ambient noise levels primarily from sound generated by the motion of mooring hardware (chains, etc.) within the testing facility. The project objectives of the acoustic measurements include quantitative estimates of range dependent root mean square sound pressure levels (SPLrms) integrated across the 60Hz - 13 kHz frequency band. Additionally, time dependent spectral analysis was focused toward identifying the frequency content of acoustic emissions generated from the testing facility.

During the acoustic recording operations, the Ocean Sentinel was located at 44$^o$ 41.835'N, 124$^o$ 07.631'W within the NETS designated facility. Acoustic measurement operations were conducted on site from 12:55 to 13:55 PDT on September 26th, 2013. Results represent an acoustic "snapshot" measurement in the vicinity of the OS limited. Significant wave heights slightly decreased during the acoustic recording operation measuring from 2.4 - 2.1 m with average periods of ~7 - 8 seconds and dominant periods up to 12 seconds. Meanwhile, wind conditions remained steady around 3 - 4 m/s gusting to 4.6 m/s. Environmental conditions experienced during this acoustic recording operation were more energetic than previous recording missions providing a good test of the newly developed acoustic drifter system.

Acoustic measurements were made using a 24-foot fiberglass hulled vessel (*Gracie Lynn* – Oregon Coast Aquarium) with a newly developed autonomous drifting underwater hydrophone (ADUH) buoy system deployed and retrieved in a series of two free floating drifts near and down-current of the Ocean Sentinel and marker buoys. Since the drift of ADUH cannot be controlled, caution was taken to deploy the recording system "downstream" to avoid entanglement. The *Gracie Lynn*'s engines and electronics were powered down during the free drifting mode in order to reduce further noise contamination. Each of two drifts with the acoustic buoy package was started as near as safely possible to the Ocean Sentinel, drifting in the dominant current direction northward for 20 minutes and ranging from 138 - 800 m of the Ocean Sentinel hull. The average drift speed of the ADUH was 0.6 m/s during each drift.

Underwater sound pressure levels were recorded around the Ocean Sentinel and NETS facility from a range of distances (138 - 800 m) using a newly developed free drifting hydrophone buoy system on September 26th, 2013. Received energy levels indicate ambient noise levels are strongly influenced by acoustic emissions from nearby vessel traffic in the area. The spectral signature of sounds generated by the motion of mooring hardware (chain noise) associated with the NETS facility was detected and identified as a set of 5 localized spectral peaks (4.6 - 5.0 kHz, 5.2 - 5.5 kHz, 9.0 - 9.4 kHz, 10.0 - 10.6 kHz, and 12.1 - 13 kHz) observed at a range of distances. Despite the contribution of these sound sources to ambient levels, SPLrms integrated across the 60Hz - 13 kHz frequency range remained below NMFS threshold criteria (120 dB) throughout the recording period. Additionally, results show a vast improvement in data quality provided by the new drifting hydrophone approach versus previous tethered recordings.

### Related Publications

Haxel J.H. (2013). Underwater acoustic measurements near the Ocean Sentinel at PMEC's North Energy Test Site (NETS) Facility. In *PMEC-NETS Annual Operations and Monitoring Report 2013*. http://hdl.handle.net/1957/57838

Haxel J.H., R.P. Dziak, H. Matsumoto. (2013). Observations of shallow water marine ambient sound: the low frequency underwater soundscape of the central Oregon coast. *Journal of the Acoustical Society of America.* 133(5), doi: 10.1121/1.4796132, 2586–2596.

## Deliverable 11.3: Annotated bibliography of environmental effects pertinent to wave energy development.

This deliverable was made superfluous by the development of TETHYS at Pacific Northwest National Labs (PNNL). TETHYS can be found at http://tethys.pnnl.gov/.

## Deliverable 11.4: Initial simulations on effects of WEC device arrays and feed information back to array design to minimize shoreline effects.

Initial simulations of WEC device arrays were conducted on an idealized, planar beach slope to draw general conclusions about the impacts of WEC arrays. The same methodology was then applied to the

NETS and SETS site in order to determine whether the general conclusions made in the idealized study were valid at field sites with realistic bathymetries. This work is discussed in the same publications listed above.

### Related Publications

O'Dea A, M.C. Haller. (2014). Analysis of the Impacts of Wave Energy Converter Arrays on the Nearshore Wave Climate. *2nd Marine Energy Technology Symposium*. Seattle, WA. http://vtechworks.lib.vt.edu/bitstream/handle/10919/49231/112-ODea.pdf?sequence=1&isAllowed=y

O'Dea A. (2014). *On the Nearshore Impact of Wave Energy Converter Arrays*. Master's thesis, Oregon State University. http://hdl.handle.net/1957/52599

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.*

## Deliverable 17.1.1: Workshop on EMF effects related to grid marine energy devices.

The *Oregon Marine Renewable Energy Environmental Science Conference* was held by the Bureau of Ocean Energy Management (BOEM) on November 28th-29th, 2012. NNMREC PI Sarah Henkel assisted during the event and was an editor for the conference proceedings. Proceedings discussing EMF effects related to marine energy technologies took place in the Immediate Impact/Short-term working group of the conference.

Initially, NNMREC was slated to host a workshop on the effects of EMF on localized marine life but this was quickly pulled into the larger BOEM conference as a high-priority working group.

Documentation surrounding this event can be found at:

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

Information on the marine biological effects of EMF related to grid-level energy production is still quite limited.

## Deliverable 17.1.2: Post installation sampling at Newport test facilities.

Pre-deployment sampling was conducted in June 2013 prior to deployment of the Ocean Sentinel, anchors and mooring systems to the North Energy Test Site (NETS). Surveys were again conducted during the active deployment in August 2013 and after removal of the device in October 2013, but with the anchors still in place. The main objective of these measurements was to determine if sediment characteristics and/or fish assemblages differed during the deployment of the device or after removal, as compared to previous observations. Specific results can be found in the *PMEC North Energy Test Site 2013 Annual Report.* An outline of sampling events is as follows:

### Water column sampling

At each station-visit vertical water-column profiles of conductivity, temperature, dissolved oxygen, pH, and depth were obtained with a Sea-Bird Electronics unit (CTD cast).

### Sediment Grabs

Sediment for grain size analysis was collected from each of the 12 stations in June, August, and October 2013. Grain sizes of the sediment were analyzed for samples from all visits using a Beckman Coulter Laser Diffraction Particle Size Analyzer (LD-PSA) to determine median grain size and percent silt/clay.

### Trawling

For collection of epifaunal invertebrates and fishes, a beam trawl was used. The beam trawl is 2 meters (m) wide by 70 centimeters (cm) high with a 3-millimeter (mm) mesh liner the entire length of the net and a tickler chain. Tows were conducted for 10 minutes, and a constant speed of ~1.5 knots was attempted.

## Related Publications

Henkel S., J. Haxel, A. Schultz, A. Hofford, S. Moran, D. Hellin, K. Hildenbrand. (2013). PMEC-NETS Annual Operations and Monitoring Report. http://hdl.handle.net/1957/57838

## Deliverable 17.1.3: Test various WEC array designs (wave and surf zone circulation simulations) to assess range of possible shoreline impacts. Identify configurations with least or no impact.

Different WEC array designs, locations, and input conditions were analyzed on an idealized beach slope using the SWAN wave model. All arrays included 60 devices in 2 staggered rows. Arrays were either widely-spaced (with 10 times the WEC diameter between devices and rows) or closely-spaced (with 4 times the WEC diameter between devices and rows), and were located either 5, 10, or 15 km offshore. Model runs with both closely-spaced and widely-spaced arrays were also conducted at both the NETS and SETS sites. This work is discussed in the same publications listed above. Nearshore circulation was not simulated, but a "threshold for nearshore impact" was established based on past field studies (Guza et al, 1986; Feddersen et al, 1998) that represents the approximate alongshore wave forcing required to result in an alongshore current of 20 cm/s. The input conditions and array designs that result in changes in nearshore forcing above the established threshold were identified.

## Related Publications

O'Dea A, M.C. Haller. (2014). Analysis of the Impacts of Wave Energy Converter Arrays on the Nearshore Wave Climate. *2nd Marine Energy Technology Symposium*. Seattle, WA. http://vtechworks.lib.vt.edu/bitstream/handle/10919/49231/112-ODea.pdf?sequence=1&isAllowed=y

O'Dea A. (2014). *On the Nearshore Impact of Wave Energy Converter Arrays*. Master's thesis, Oregon State University. http://hdl.handle.net/1957/52599

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.*

## Deliverable 17.1.4: Complete work on potential shoreline effects of WEC arrays.

Potential shoreline effects from WEC array placement include altered sediment erosion or collection and diminished kinetic wave energy in the spatial region immediately behind the array. The O'Dea line of research and publications represents the most complete understanding of the impact of tidal arrays on coastal and near-coastal (surf zone) environments made available under this grant.

In addition to sedimentation and erosion effects, wave climate effects in regions surrounding hypothetical WEC arrays are important to shoreline environmental effects. These topics are discussed at length in the O'Dea line of research funded through this grant.

### Related Publications

O'Dea A, M.C. Haller. (2014). Analysis of the Impacts of Wave Energy Converter Arrays on the Nearshore Wave Climate. *2nd Marine Energy Technology Symposium*. Seattle, WA. http://vtechworks.lib.vt.edu/bitstream/handle/10919/49231/112-ODea.pdf?sequence=1&isAllowed=y

O'Dea A. (2014). *On the Nearshore Impact of Wave Energy Converter Arrays*. Master's thesis, Oregon State University. http://hdl.handle.net/1957/52599

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.*

## Deliverable 17.2.1: Conduct passive acoustic characterization of a full-scale tidal turbine to assess relationship between noise and power generation state.

Passive acoustic characterization of the ORPC RivGen turbine was conducted in August 2014 using A-SWIFT drifters. More than a hundred drifting measurements were obtained around RivGen under a range of operating set points. Measurements demonstrate that the primary mechanisms for sound production are generator tones, a misaligned drive shaft (periodic, broadband click centered around 2 kHz), and blade vibration. Turbine sound is primarily restricted to frequencies less than 5 kHz and, in the absence of drive shaft misalignment would be restricted to frequencies less than 1 kHz. At the closest point of approach, for an optimally operating turbine (i.e., peak power generation), one-third octave levels were elevated by up to 40 dB relative to braked conditions. Broadband spatial patterns suggested relatively limited sound directivity. This study highlighted the benefits of using Lagrangian drifters to characterize turbine sound (e.g., flow noise mitigation, spatially-resolved acoustic fields) and challenges (e.g., positional accuracy, self-noise contamination).

### Related Publications

Polagye B., Murphy, P. (2015). Acoustic characterization of a hydrokinetic turbine. *11th European Wave and Tidal Conference*. Nantes, France.
https://depts.washington.edu/nnmrec/docs/Polagye_Murphy_EWTEC2015.pdf

## Deliverable 17.2.2: Develop simple, open-source models for pre-installation estimates of acoustic effects from tidal turbines.

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. Using long-term passive acoustic monitoring in Admiralty Inlet, Bassett et al. (2013) and Bassett et al. (2014) demonstrated the importance of bedload sediment transport and turbulence, respectively.

The simplicity of the model translated to a relatively intuitive comprehension of its results by regulators for the Snohomish PUD tidal energy demonstration project. However, peer reviewers felt that the simplicity of elements of the model, specifically the use of empirical transmission loss, were not defensible and recommended the use of higher-fidelity acoustic propagation models. Consequently, the existing version of the model has not been released, pending a comparison of parabolic equation modeling to empirical transmission loss.

### Related Publications

Bassett C., J. Thomson, P. Dahl, B. Polagye. (2014). Flow noise and turbulence in two tidal channels. *Journal of the Acoustical Society of America.* 135.

Bassett C., J. Thomson, B. Polagye. (2013). Sediment-generated noise and bed stress in a tidal channel. *Journal of Geophysical Research.*118.

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). *In revision.*

## Deliverable 17.2.3: Develop a framework/checklist for local modelers to verify the fitness of their models to evaluate and quantify the extractable tidal resource.

Inland coastal waters of the State of Washington, United States, are fjord-like in character and feature passages where tidal currents with speeds of 3 m/s or greater occur. Combined with close proximity to the major metropolitan area of Seattle and easy access to the power grid, the region is a prime candidate within the United States for tidal power generation. A new three-dimensional (3D) model of tidal circulation of these waters has been implemented. The model is based on Stanford University's SUNTANS code, and covers the eastern Strait of Juan de Fuca, Puget Sound, San Juan and Channel Islands, and the southern Georgia Basin with an unstructured triangular mesh of 250 m average resolution. It is forced with tidal currents from a regional tidal model along open boundaries. Barotropic tidal response is calibrated against compiled tidal data for the region; the system response is characterized in terms of sea surface height variability and energy dissipation. The model can simulate tides with quantitative accuracy within Puget Sound, but it over-predicts tidal range and under-predicts currents in the waterways leading up to the Main Basin of the Sound. Future plans for the model include extension of the model domain for the entire Georgia Basin, incorporation of partial bottom cells and baroclinic processes and improvements in bathymetry.

A highly idealized model of an ocean-fjord system, in which the tide is forced astronomically by the gravitational force of the moon, is used to study effects of localized tidal energy extraction on regional and global tides. The modeled system is energetically complete in the sense that the model does not have an open boundary and the integrated energy balance has no exchange term with the outside ocean. Both normal and tidally near-resonant fjords are considered. A series of energy extraction experiments is performed to establish the scaling between energy extraction and changes in the tidal parameters with in the estuary and the surrounding ocean. These experiments confirm previous theoretical results on the scaling. At maximum extraction, approximately half the energy extracted is redirected from natural dissipation within the fjord, while the remainder is drawn anew from the ocean. The experiments are then repeated with a pair of subdomain models of different domain extent, for which tides sampled from the complete model are used as boundary conditions. The scaling relationship between extraction and tidal parameters in the subdomain models agrees with that of the full-domain model, but the estimate of the maximum extractable energy differ by up to 27%.

## Related Publications

Kawase M., K.M. Thyng. (2010). Three-dimensional hydrodynamic modelling of inland marine waters of Washington state, United States, for tidal resource and environmental impact assessment. *IET Renewable Power Generation*. 4, 568-578.

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*. 8. Device and environmental modelling. http://hdl.handle.net/1957/59021

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix F: Deliverables for Tasks: 6, 12, 18**
***Increased Reliability and Survivability of Marine Power Technologies***

**DOE Award Number: DE-FG36-08GO18179-M001**
**Period Covered: 9/15/2008 – 3/14/2016**
**Delivered: June 30, 2016**

**Northwest National Marine Renewable Energy Center**

**Oregon State University**
**University of Washington**

## Deliverables



## Deliverable 6.1: Evaluation of existing high-sea state survival mechanisms applicable to WEC devices.

Adam Brown undertook preliminary work on reliability (Brown et al. 2008) and survivability (Brown et al. 2010) of wave energy convertors. In this early research on survival mechanisms, we realized there was a large gap in knowledge about what constitutes a "high sea state". We could not evaluate specific survival mechanisms without more knowledge about the sea states the devices needed to survive. With DoE's approval, we re-scoped the project, shifting some project focus from mechanism design, modeling and testing to extreme event characterization.

Initial work by Pukha Lenee-Blum (Lenee-Bluhm et al. 2011), based on NDBC data, characterized the wave resource in the Pacific Northwest from a design standpoint. This provided information on the expected wave climate, including wave height, period and directionality. This work formed the basis for IEC TS 62600-101, Marine energy - Wave, tidal and other water current converters - Part 101: Wave energy resource assessment and characterization.

Justin Hovland (Hovland et al. 2010) analyzed the NBDC data to identify storm events, and from those events attempted to identify the occurrence of breaking waves. One of the main take-aways from this work was the realization that NDBC buoys are not designed to detect breaking waves. Hovland found a fuzzy “steepness” limit to the height/period ratios recorded by the NDBC buoys. One possible reason for this steepness limit is that waves beyond this limit are breaking.

### Related Publications

Brown A., R. Paasch, I.Tumer, P. Lenee-Bluhm, J. Hovland. (2014). Towards a Definition and Metric for the Survivability of Ocean Wave Energy Converters. *ASME 4th International Conference on Energy Sustainability*. Phoenix, AZ. http://proceedings.asmedigitalcollection.asme.org/pdfaccess.ashx?ResourceID=5288390&PDFSource=13

Brown A., I. Tumer, R. Paasch. (2008). Early Stage Failure Modeling and Safety Analysis Applied to the Design of Wave Energy Converters. *2008 ASME Design Theory and Methodology Conference*. New York, NY.

Hovland J., R. Paasch, M. Haller. (2010). Characterizing Dangerous Waves for Ocean Wave Energy Converter Survivability. *29th ASME International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2010)*. Shanghai, China. http://hdl.handle.net/1957/59022

Lenee-Bluh P., R. Paasch, H.T. Ozkan-Haller. (2011). Characterizing the wave energy resource of the US Pacific Northwest. *Renewable Energy* 36: 2106 – 2119.

## Deliverable 6.2: Evaluation of existing high-sea state survival mechanisms applicable to WEC devices.

To determine the state of the knowledge on ocean biofouling prevention through the use of biocidal and active electrochemical coatings, a search of the open technical literature pertaining to the topic was carried out and compiled. The biocidal coatings work for major part describes the use of and, more recently, negative consequences of the use of tin based biocides, and of the recent development of Cu based coatings, commonly boosted through the use of an herbicide like diuron in its formulation. The work describing the use of electrochemical biofouling prevention is fairly sparse and is mainly focused on a few journal articles from researchers in Japan. The work is documented in Matthew Delaney’s MS thesis in Chapter 2.

### Related Publications

Delaney M. (2011). Study of Graphite-Polyurethane Composite Thin Film Electrodes for their Use in Electrochemical Antifouling Systems. Master’s thesis, Oregon State University. http://hdl.handle.net/1957/23278

## Deliverable 6.3: An initial experimental approach to test electrochemical antifouling systems.

In order to enable field work using electrochemical biofouling prevention, an inexpensive design for a field deployable potentiostat that could be constructed in the lab was developed, as was a rugged and inexpensive Ag|AgCl (seawater) reference electrode. The potentiostat design potentially allows multiple potentiostats to operate under the same circuit and in the same electrochemical cell for higher throughput of electrochemical experiments. One low cost potentiostat was constructed and qualified against a well-known electroactive species (Ferrocyanide/Ferricyanide couple) to verify suitability for the application. The reference electrodes were similarly tested to verify suitability of the resulting data. A watertight housing that can be field deployed was then constructed, and the system used for experiments at HMSC.

Conductive paints able to be coated on large surfaces and capable of acting as the electrochemical biofouling prevention coating electrode were developed from a combination of graphite and commercial urethane coatings. The performance of the electrochemical biofouling prevention technology was tested using 10 x 5 $cm^2$ test coupons, and compared with commercial (conventional biocidal) coatings, and using an unenergized electrochemical prevention coating as a blank experiment, demonstrating the ability of the electrochemical technology to perform as well as current biocidal coatings.

The final potentiostat design is given in Appendix A of Matthew Delaney's thesis, and potentiostat qualification results, conductive and electroactive coating, and initial results from coating experiments are given in Chapter 4 of Matthew Delaney's MS thesis.

### Related Publications

Delaney M. (2011). Study of Graphite-Polyurethane Composite Thin Film Electrodes for their Use in Electrochemical Antifouling Systems. Master's thesis, Oregon State University. http://hdl.handle.net/1957/23278

## Deliverable 12.1: Develop, model and test survival mechanisms for direct drive WEC devices.

Kelley Ruehl (Ruehl et al. 2010) & (Ruehl et al. 2013) developed several time domain models of heaving point absorbers. This modeling work formed the foundation for WEC-Sim. Sean Casey (Casey 2013) extended this work, taking into account different control strategies and the impact on extreme loads within the power takeoff system. Chad Stillinger (Stillinger et al. 2011) looked at the influence of control strategies on rolling-element bearing failure within wave convertors. Stephen Meicke (Meicke et al. 2012 and Koopmans et al. 2011) characterized the wear rate and life of sea-water immersed polymer bearings operating under various loading regimes.

## Related Publications

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

Koopmans M.T., S. Meicke, I.Y. Tumer, R. Paasch. (2011). Experimental Polymer Bearing Health Estimation and Test Stand Benchmarking for Wave Energy Converters. *Annual Conference of the Prognostics and Health Management Society*. Montreal, QB.

Meicke S., R. Paasch. (2012). Seawater Lubricated Polymer Journal Bearings for Use in Wave Energy Converters. *Renewable Energy* 39: 463-470.

Ruehl K., R. 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. http://energy.sandia.gov/wp-content/gallery/uploads/130911c.pdf

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.

Stillinger C., T.K.A. Brekken, A. von Jouanne, R. Paasch, D. Naviaux, K. Rhinefrank, J. Prudell, A.A. Schacher, E. Hammagren. (2011). WEC prototype advancement with consideration of a real-time damage accumulation algorithm. *PowerTech*. Trondheim, Norway.

## Deliverable 12.2: Develop low cost, robust electrochemical protection system capable of field deployment.

By modifying the design of the low cost field deployable potentiostat such that the applied potential at the working electrode is simply set by applying a simple voltage to the electric power module, as opposed to using a microcontroller based device, a series of devices were constructed and housed in a water resistant enclosure, which was then used for experimental work. To avoid need to attach the device to the general electrical power supply, a battery based power supply was developed and built to energize the experiments. Details of the developed and implemented experimental system are summarized in Malachi Bunn's dissertation in section 3.5, and in the *Research and Ocean Testing Solutions to Advance the Wave Energy Industry* paper.

## Related Publications

Bunn M. (2015). Aging and Performance Evaluation of Marine Antifouling Coatings. PhD dissertation, Oregon State University. http://hdl.handle.net/1957/56890

von Jouanne A., T. Brekken, T. Lettenmaier, E. Amon, S. Moran, A. Yokochi A. (2014). Research and Ocean Testing Solutions to Advance the Wave Energy Industry. *IEEE Power and Energy Society General Meeting*. National Harbor, MD.

## Deliverable 12.3: Short and long term deployment of test samples in Yaquina Bay for system evaluation.

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 Hatfield Marine Science Center (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 $mA.m^{-2}$. This implies that to protect a discus buoy with a diameter of 10 meters (yielding an immersed surface area of approx. 80$m^2$) you would need to apply a current of 0.8 A; assuming a required potential between the hull and a counterelectrode of about 2V (1.1V vs. Ag/AgCl + 0.2V + ~0.7V overpotential for counterelectrode reaction) this is a load of 1.6W, a negligible fraction of the multi-kW power production expected from a wave energy conversion device.

Results are documented in Malachi Bunn's dissertation and summarized in the papers *Electrochemical Antifouling Technology for Replacement of Heavy Metal and Organic Biocides in Marine Hydrokinetic Energy Generation* and *Wave Energy Testing Using the Ocean Sentinel Instrumentation Buoy Including Testing of Materials and Technologies for Bio-Fouling Resistant Surfaces*.

### Related Publications

Bunn, M. (2015). Aging and Performance Evaluation of Marine Antifouling Coatings. PhD dissertation, Oregon State University. http://hdl.handle.net/1957/56890

Bunn M., A. Yokochi, A. von Jouanne. (2014). Electrochemical Antifouling Technology for Replacement of Heavy Metal and Organic Biocides in Marine Hydrokinetic Energy Generation. *SusTech 2014*.

von Jouanne A., T Lettenmaier, E. Amon, S. Moran, M. Bunn, A. Yokochi. (2013). Wave Energy Testing Using the Ocean Sentinel Instrumentation Buoy Including Testing of Materials and Technologies for Bio-Fouling Resistant Surfaces. *Ocean Energy Special Issue of the Shore and Beach Journal*. http://hdl.handle.net/1957/56890

## Deliverable 12.4: Initial report on benefits of composite materials for tidal turbines and ocean energy systems.

A screening test was conducted to identify composite material system(s) that exhibit good long-term durability when continuously exposed to salt-water. Four composite material systems were considered; panels of these four material systems were submerged and exposed to in situ conditions at a potential tidal energy site. A reduction in shear modulus following exposure was observed for all four material systems considered. Moreover, these results demonstrated that elevated temperature causes shear modulus degradation and can therefore be used as an accelerating agent.

### Related Publications

Ogg A. (2011). Screening Tests of Composites for use in Tidal Energy Devices. Master's thesis, University of Washington. http://hdl.handle.net/1773/17061

## Deliverable 18.1: Identification of best anti-fouling performers in real ocean energy system geometries.

In order to measure performance of the technology in real ocean conditions, experiments intended to compare the performance of the electrochemical biofouling prevention coatings with those of conventional biofouling prevention technologies were deployed along with past deployments of the ocean sentinel, but due to severe weather in both campaigns, the experiments were destroyed. To produce data for systems where long electrical distances may exist between the working electrode and the counter-electrode in an actual ocean energy device, a flow through system was constructed. The results confirm that for adequate prevention of marine organism growth in such geometries, that 1.12V vs Ag|AgCl (seawater) is needed, with an operating current density of 28(7)μA/cm$^2$.

Results are documented in Malachi Bunn's dissertation and summarized in the papers *Electrochemical Antifouling Technology for Replacement of Heavy Metal and Organic Biocides in Marine Hydrokinetic Energy Generation* and *Wave Energy Testing Using the Ocean Sentinel Instrumentation Buoy Including Testing of Materials and Technologies for Bio-Fouling Resistant Surfaces*.

### Related Publications

Bunn, M. (2015). Aging and Performance Evaluation of Marine Antifouling Coatings. PhD dissertation, Oregon State University. http://hdl.handle.net/1957/56890

Bunn M., A. Yokochi, A. von Jouanne. (2014). Electrochemical Antifouling Technology for Replacement of Heavy Metal and Organic Biocides in Marine Hydrokinetic Energy Generation. *SusTech 2014*.

von Jouanne A., T Lettenmaier, E. Amon, S. Moran, M. Bunn, A. Yokochi. (2013). Wave Energy Testing Using the Ocean Sentinel Instrumentation Buoy Including Testing of Materials and Technologies for Bio-Fouling Resistant Surfaces. *Ocean Energy Special Issue of the Shore and Beach Journal*. http://hdl.handle.net/1957/56890

## Deliverable 18.2: Models and engineering protocols for predicting coatings behaviors in long-term deployments.

Accelerated aging of electrochemical biofouling prevention coatings was measured using current density as the accelerating factor: by increasing the current density to 3.16mA/cm$^2$ (a value limited by the electrochemical window for water, since higher applied currents cause water splitting, and creating electrode damage due to mechanisms different from those postulated for the oxidation of chloride to hypochlorite) we could achieve several years worth of equivalent aging due to electrochemical reaction damage. The measurements were performed on the same graphite/urethane composite coatings the remainder of the work was carried out on. No significant changes were observed on the exchange current density nor the charge transfer coefficient for the coatings under test. The results of the accelerated aging experiments are described in section 5.6 of Malachi Bunn's dissertation and in the paper *Electrochemical Antifouling Technology for Replacement of Heavy Metal and Organic Biocides in Marine Hydrokinetic Energy Generation*.

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 incorporates 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. The series of differential equations are described in section 3.6 and in chapter 4 of Malachi Bunn's dissertation and in the paper "Electrochemical Reactor Modeling and the Determination of Minimum Operating Parameters for Conductive Paint Antifouling Systems".

In order to understand the magnitudes of the electrical fields induced in seawater due to seawater flow around cables carrying electrical power from the ocean energy buoys, experiments and mathematical equations were developed for this problem as well. Experimental and computational results were in agreement, and indicate that, for example, a current of 10A AC at a frequency of 60Hz will induce an electric field of about 0.1 mV/m at a distance of 5cm from the cable, and that this field magnitude quickly falls to negligible values by the time a distance of about 10 cm is achieved. These results are documented in the publication "*Wave Energy Power Transmission Lines: Electric and Magnetic Field Propagation*".

## Related Publications

Bunn, M. (2015). Aging and Performance Evaluation of Marine Antifouling Coatings. PhD dissertation, Oregon State University. http://hdl.handle.net/1957/56890

Bunn M., A. Yokochi, A. von Jouanne. (2014). Electrochemical Antifouling Technology for Replacement of Heavy Metal and Organic Biocides in Marine Hydrokinetic Energy Generation. *SusTech 2014*.

Pommerenck J., J. Pommerenck, A. von Jouanne, A. Yokochi. (2014). Wave Energy Power Transmission Lines: Electric and Magnetic Field Propagation. *SusTech 2014*.

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.* Washington, DC. http://www.nationalhydroconference.com/index/post-show/2015-mets-presentations.html

## Deliverable 18.3: Model and Simulate effects of breaking waves on WECs.

Stephen Meicke (Meicke et al. 2011) modeled both the Columbia Power 1/15$^{th}$ scale SeaRay wave convertor and a large wave tank within LS-DYNA to investigate the structural loads induced in the wave convertor due to breaking waves. Meicke also instrumented the SeaRay with strain gauges in order to collect validating physical load data, but this effort was unsuccessful.

### Related Publications

Meicke S. (2011). Hydro-elastic Modeling of a Wave Energy Convertor using the Arbitrary Lagrangian-Eulerian Finite Element Method in LS_DYNA. Master's thesis, Oregon State University. http://hdl.handle.net/1957/23455

## Deliverable 18.4: Investigate WEC device topologies for increased reliability and survivability.

Adam Brown (Brown et al. 2013, Brown et al. 2014 & Brown et al. 2015) designed, manufactured and ocean tested an instrumented spherical buoy specifically designed to detect breaking waves in the deep-water open ocean. His work also discusses the effects of breaking waves on wave energy convertor reliability and survivability.

### Related Publications

Brown A., R. Paasch, B. Batten. (2013). Wave Energy: Considering the Waves. *Shore and Beach*. Vol. 81, no. 4.

Brown A., R. Paasch, B. Batten. (2014). Fatigue Life Distribution of a Simple Wave Energy Converter. *2$^{nd}$ Marine Energy Technology Symposium*. Seattle, WA. http://vtechworks.lib.vt.edu/handle/10919/49224

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

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix G: Deliverable for Task 19:** ***Site Selection and Outreach***

**DOE Award Number: DE-FG36-08GO18179-M001**

**Period Covered: 9/15/2008 – 3/14/2016**

**Delivered: June 30, 2016**

**Oregon State University**

**University of Washington**

## Deliverable 19.1: GPS Coordinates of the PMEC site that meets the needs of the industry as defined by engineering analysis and requirements and accepted by the local community.

The collaborative siting process for PMEC-SETS built on NNMREC's earlier experiences in community engagement. This process was initiated through the feasibility study that was done to satisfied Deliverable 16.1.2, and 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 un-supportive of ocean energy, e.g., commercial fishermen. The process also created many new partnerships with local businesses, and these relationships will now be passed on to developers. The ultimate site selection for PMEC-SETS was made after review of two solicited proposals from the communities of Newport and Reedsport (Newport, 2012, Reedsport, 2012).

The ocean location for the project site was chosen in consultation with a group of local fishermen, Fishermen Involved in Natural Energy (FINE), which identified a 6 square nautical mile "study area" off the coast of Newport that the members felt would be a suitable and acceptable area within which to locate PMEC-SETS based on their extensive knowledge of the local marine environment. Based on the area identified by FINE, NNMREC-OSU submitted a research lease application to BOEM.

NNMREC-OSU subsequently conducted site-specific marine surveys and gathered information from agencies and stakeholders to characterize the physical and biological conditions of the area. This information, as well as engineering and testing client requirements were used to down-select to a 2 square nautical mile PMEC-SETS test site.

The coordinates for the corners of the 2 square nautical-mile Project site are below:

- NW: 44° 35' 00.00"N 124° 14' 30.00"W
- NE: 44° 35' 02.75"N 124° 13' 06.17"W
- SE: 44° 33' 02.75"N 124° 12' 58.51"W
- SW: 44° 33' 00.00"N 124° 14' 22.41"W

The Project site coordinates will be confirmed by final marine surveys. Although it is possible that the site boundaries could be shifted slightly based on the final survey results, the site coordinates would not extend beyond the lease area; accordingly, there would be no change in the potentially affected resources and potential effects considered.

### Related Publications

Community of Newport. (2012). Proposal: Newport Site for the Pacific Marine Energy Center. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

Community of Reedsport. (2012). Reedsport Proposal to Host the Northwest National Marine Renewable Energy Center's Pacific Marine Energy Center. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

Pacific Energy Ventures. (2011). Feasibility Study for a Grid Connected Pacific Marine Energy Center. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix H: Deliverables for Task 20:** ***Engineering Studies and Underlying Analysis***

**Subtasks 20.1** ***Market and Supply Chain Analysis*****; 20.2** ***Engineering Analysis and Pre-Design;*** **20.3** ***Outreach and Engagement***

**DOE Award Number: DE-FG36-08GO18179-M001**

**Period Covered: 9/15/2008 – 3/14/2016**

**Delivered: June 30, 2016**


**Oregon State University**

**University of Washington**

## Deliverables



## Deliverable 20.1.1: Market Analysis for User Needs.

A market analysis report was written by Garrad Hassan America, Inc. and published by the Oregon Wave Energy Trust under this award. GL Garrad Hassan published this report in 2013 at the request of the Northwest National Marine Renewable Energy Center (NNMREC) in accordance with this grant deliverable.

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 U.S. 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 has already been selected, there is 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

### Related Publications

GL Garrad Hassan. (2013). Market Analysis Report for the Pacific Marine Energy Center South Energy Test Site. http://oregonwave.org/oceanic/wp-content/uploads/2013/05/Market-Analysis-for-PMEC-Wave-Energy-Test-Facilities_B_PUBLIC.pdf

## Deliverable 20.1.2: Supply Chain Analysis

In 2012, the location for the establishment of the grid-connected wave energy test site for the Pacific Marine Energy Center (PMEC) was announced to be off the coast of Newport, Oregon. This location sits near the existing PMEC off-grid test site, which lies off 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 Northwest National Marine Renewable Energy Center (NNMREC) operates these facilities.

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 are based in Newport, Oregon.

There were three primary aims of this study:

- 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. 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. Existing supply chain data (see below) with 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. Finally, 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:

- this 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.

The supply chain analysis report was compiled by Aquatera Ltd. on behalf of OWET under this award.

### Related Publications

Aquatera Ltd. (2014). Oregon Wave Energy Supply Chain Analysis. http://oregonwave.org/oceanic/wp-content/uploads/2013/05/Oregon-Supply-Chain-Analysis_FINAL.pdf

## Deliverable 20.2.1: PMEC Development Plan

The European Marine Energy Centre's *Conceptual Design Report for PMEC Facility* outlined the preliminary physical development needs of a facility like PMEC located in Oregon. NOTE: this report formed the basis for additional efforts completed under award number DE-EE-0006518. The following is a brief summary of the EMEC report:

This report described, at a conceptual level, a proposed design for a test facility for wave energy converters for OWET/NNMREC 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 at the time of writing, the ideas and concepts outlined in this report are relevant irrespective of the particular site. Now a site selection has been made, some aspects will need further consideration to take into account specific site-related requirements.

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.

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.

### Related Publications

European Marine Energy Centre. (2013). Conceptual Design Report for PMEC Facility. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

## Deliverable 20.2.2: Pre-design Documents, Detailed Cost Estimates, Operation & Management Plan.

In 2013, EMEC created three reports at the request of NNMREC which together serve as the fulfillment for this deliverable. The *PMEC Cost Calculation Report* and the *Site Description for PMEC Facility* are summarized below.  NOTE: these reports formed the basis for additional cost calculations and facility design efforts completed under award number DE-EE-0006518.

### PMEC Cost Calculation Report

The site that the PMEC test center will be installed is at 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. 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.

A total area of 93 x 61 meters (305 x 200 feet approx.) is deemed sufficient to contain the substation and a lay-down area for developers to use, the Visitors Centre and adequate space for parking and a turning space for large articulated vehicles.

### Related Publications

European Marine Energy Centre. (2013). Conceptual Design Report for PMEC Facility. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

European Marine Energy Centre. (2013). PMEC Cost Calculation Report. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

European Marine Energy Centre. (2013). Site Description for PMEC Facility. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

## Deliverable 20.2.3: PMEC Business Plan

In 2011, a business plan was created for the PMEC-NETS site. As part of the Task 20.2 deliverable, NNMREC commissioned OWET to develop a marketing plan for PMEC-SETS. Until PMEC-SETS is closer to being operational and requirements are known (e.g., for environmental monitoring - what monitoring and how often) it is difficult to further develop the business plan. The PMEC-NETS business plan and the PMEC-SETS marketing plan will be used to produce a detailed business plan.

### Related Publications

Northwest National Marine Renewable Energy Center. (2011). Draft Business Plan for NNMREC's Mobile Ocean Test Berth. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

Oregon Wave Energy Trust. (2016). PMEC-SETS Marketing Plan. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

## Deliverable 20.3.1: Quarterly Reporting of Outreach and Engagement Activities.

In addition to the discussion on site selection and outreach in the final report that this set of deliverables accompanies, quarterly reports of outreach and engagement activities were provided to DOE.

Moreover, a database of available fishing vessels was constructed that can be used to support NNMREC research and testing operations going forward.

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix I: Deliverables for Task 21: *Permitting***

**Subtasks 21.1 *Permitting Strategy*; 21.2 *Site Characterization*; 21.3 *Utility Connection***

**DOE Award Number: DE-FG36-08GO18179-M001**

**Period Covered: 9/15/2008 – 3/14/2016**

**Delivered: June 30, 2016**

**Oregon State University**

**University of Washington**

## Deliverables



## Deliverable 21.1.1: Permitting applications filed, working relationships with necessary permitting agencies (FERC, USACE, DSL/BOEM, ODFW, NOAA)

### Consultation History

In conjunction with the community site selection process, NNMREC began engaging with both Federal Energy Regulatory Commission (FERC) and the Bureau of Ocean Energy Management (BOEM) in fall 2012 to share information about the Project and help prepare for the regulatory process. NNMREC held conference calls with each agency individually to share initial information about the Project, followed by a conference call with FERC and BOEM to discuss the licensing and leasing processes. In January 2013, NNMREC formed an advisory team comprised of federal and state agencies involved in the PMEC-SETS authorization process, including the National Marine Fisheries Service (NMFS) and US Fish & Wildlife Service (USFWS), as well as non-governmental organizations representing stakeholder interests, to collectively explore the Project and identify key regulatory and environmental considerations, including potential impacts to Endangered Species Act (ESA)-listed species and critical habitat. This advisory group is called the Collaborative Workgroup (CWG). See below for CWG members.

A primary focus of the CWG was on how the Project would meet regulatory standards and undertake approval processes under the Federal Power Act (FPA) and other federal and state approvals. As part of these efforts, NNMREC and other members of the CWG agreed that the Alternative Licensing Process (ALP) would be the most appropriate FPA licensing process for PMEC-SETS because it would allow the CWG members to work cooperatively toward the ultimate NNMREC licensing proposal. Additional details about the establishment of the CWG, as well as the process used to develop and reach consensus, are provided in the Request to Use the ALP and the associated Communications Protocol that were filed with the Pre-Application Document (PAD) in April 2014. All filed documents can be found at PMEC.US. In a notice dated May 27, 2014, FERC designated NNMREC as FERC's non-federal representative for carrying out informal consultation pursuant to Section 7 of the ESA. NMFS identified 35 federally listed species under its jurisdiction that may occur within the vicinity of the Project (letter from NMFS to NNMREC dated May 22, 2015), including six species of whales, four species of sea turtles, 23 species of salmonids, one species of sturgeon, and one species of smelt (eulachon). Critical habitat has been proposed or designated for 15 of these species, though the only designated critical habitats that overlap the Project footprint are for green sturgeon and leatherback sea turtle. FWS identified 3 federally listed bird species under its jurisdiction that may occur in the vicinity of the Project (letter from FWS to FERC dated August 1, 2014). Through interagency meetings related to the FPA licensing process, NNMREC has been coordinating with

NMFS and other resource agencies to identify potential Project impacts, the likelihood of harm from those impacts on ESA-listed species and their habitats, and the need for measures to mitigate or monitor species' interactions with Project components.

A draft PDEA was developed and sent to NMFS and other resource agencies on March 24, 2015. Among other things, the draft PDEA analyzed potential effects of the Project on threatened and endangered species and their habitats. Comments were received from NMFS on May 22, 2015 and NNMREC incorporated those comments in the draft PDEA and this BA as appropriate. In addition to engaging one-on-one with interested parties, NNMREC has held a number of meetings with NMFS and other agencies and stakeholders since January 2013. On September 4, 2015, the NNMREC team shared with NMFS an example analysis of "Changes to Marine Community Composition and Behavior" from the draft BA to allow NMFS to review for general organization and level of analysis. On October 8, 2015, NMFS provided feedback and NNMREC has incorporated this feedback into the development of the draft BA.

## Filed Documents – these are available online at pmec.us

| Item | Date |
|---|---|
| Unsolicited Request for Renewable Energy Research Lease | 10/29/2013 |
| Request for Competitive Interest | 3/24/2014 |
| Request for Competitive Interest Public Comments | 4/23/2014 |
| Determination of No Competitive Interest | 6/20/2014 |
| Notice of Intent to File Original License | 4/15/2014 |
| Notice of Intent and Preliminary Application Document Letter | 4/15/2014 |
| Request to Use Alternative Licensing Procedures & Communications Protocol | 4/15/2014 |
| Preliminary Application Document | 4/15/2014 |
| Consultation letter to Confederated Tribes of Siletz Indians | 4/25/2014 |
| Consultation letter to Confederated Tribes of Grand Ronde | 4/25/2014 |
| Authorization to Use ALP | 5/27/2014 |
| Notice of Intent to File License Application | 5/27/2014 |
| Errata Notice | 5/28/2014 |
| Errata Notice | 6/11/2014 |
| Acceptance as Cooperating Agency - Army Corps of Engineers | 7/3/2014 |
| Acceptance as Cooperating Agency - Bureau of Ocean Energy Management | 7/28/2014 |
| Scoping Document 1 | 6/5/2014 |
| Notice of Scoping Meeting | **5/5/2014** |
| Scoping Meeting Transcript July 9, 2014 1pm | 8/4/2014 |
| Notice of Scoping Meeting | 8/4/2014 |
| Scoping Meeting Comments | Various |
| Scoping Document 2 | 9/16/2014 |
| FERC Six-month Report 1 | 10/15/2014 |
| FERC Six-month Report 2 | 4/15/2015 |

## Collaborative Workgroup members

| Type | Organization | Representative | Title |
|---|---|---|---|
| Federal Agencies | Bureau of Ocean Energy Management | Greg Sanders | Wildlife Biologist |
| | | Jean Thurston | Renewable Energy Program Specialist |
| | | Lisa Gilbane | Benthic Biologist |
| | Federal Energy Regulatory Commission | Jim Hastreiter | Fish Biologist |
| | National Marine Fisheries Service | Keith Kirkendall | Supervisory Natural Resource Specialist |
| | | Kim Hatfield | Biologist |
| | NOAA Office of General Counsel | Jane Hannuksela | Attorney Advisor |
| | US Fish & Wildlife Service | Stefanie Stavrakas | Alternative Energy/404 Coordinator |
| | | Roberta Swift | Seabirds, Migratory Birds & Habitat Program |
| | Environmental Protection Agency | Bridgette Lohrman | Ecologist |
| | US Army Corps of Engineers | Brad Johnson | Portland Regulatory |
| | | William Abadie | Acting Chief, Portland Permits Section |
| | US Department of Energy | Jocelyn Brown-Saracino | Senior Analyst |
| | US Coast Guard | Kenneth Lawrenson | MSE, Naval Architecture |
| State Agencies | Oregon Department of Fish & Wildlife | Delia Kelly | Ocean Energy Coordinator |
| | Oregon Department of State Lands | Carrie Landrum | Resource Coordinator |
| | | Charles Perino | Proprietary Coordinator |
| | | Lori Warner-Dickason | Operations Manager |
| | Oregon Department of Environmental Quality | Marilyn Fonseca | 401 Hydro Water Quality Assessments |
| | | Sara Christensen | 401 Certification Coordinator |
| | Oregon Parks & Recreation Department | Laurel Hillman | Ocean Shore Planner |
| | | Tony Stein | Central Coast - Lincoln City |
| | | Dennis Griffin | State Archeologist (SHPO) |
| | Oregon Department of Land Conservation & Development | Paul Klarin | Marine Affairs Coordinator |
| | | Heather Wade | Coastal State-Federal Relations Coordinator |
| | Office of the Governor | Gabriela Goldfarb | Natural Resources Advisor |
| | Oregon Department of Energy | - | - |
| Community / Local Government | City of Newport | Derek Tokos | Community Development Director |
| | Lincoln County | Wayne Belmont | County Counsel |
| | Port of Toledo | Bud Shoemake | Port Manager |
| | FINE/Port of Newport | Walter Chuck | Port Commissioner |
| | Newport Community | Paul Amundson | Citizen |
| Tribes | Confederated Tribes of the Siletz | Tracy Bailey | Energy Manager |
| NGOs | Surfrider | Charlie Plybon | Oregon Policy Manger |
| | Oregon Shores | Robin Hartmann | Ocean Program Director |
| | Oregon Wave Energy Trust | Jason Busch | Executive Director |
| Project Team | Northwest National Marine Renewable Energy Center | Belinda Batten | Director |
| | | Dan Hellin | Assistant Director for Test Operations |
| | | Sarah Henkel | Environmental Research Director |
| | Pacific Energy Ventures | Justin Klure | Managing Partner |
| | Stoel Rives | Cherise Gaffney | Partner |
| | HDR Engineering | Peter Browne | Senior Consultant |
| | H. T. Harvey & Associates | Sharon Kramer | Principal |
| Facilitator | Sapere Consulting | Kevin Kytola | Vice President |

## Related Publications

Pacific Energy Ventures. (2013). PMEC-SETS Regulatory Framework and Strategy. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

## Deliverable 21.2.1: Baseline characteristics of PMEC site for key parameters.

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) 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 Draft and Final License Applications. Additionally, these study results, along with existing information and data, will help inform final Project siting and 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 not to be necessary through the permitting process. 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.

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. The table below summarizes the status of the site characterization components.

Table I.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 the Technical 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 and data exist. | Study not undertaken but existing vessel AIS data mapped. | - |
| EMF | Postponed as part of permitting process. | Post-installation monitoring is planned. | - |

### Related Publications

NNMREC. (2016). Site Characterization Report. *Uploaded to the EERE Project Management Center under award number DE-EE-0006518. File name: PMEC-SETS_M7.1.1_Site_Characterization_Report_2016.pdf.*

Goldfinger C., C. Romsos, B. Black. (2014). Survey and Analysis of the Surficial Geology and Geophysics in the SETS Test Site area and Associated Cable Routes in the Vicinity of Seal Rock, Oregon. *Uploaded to the EERE Project Management Center under award number DE-EE-0006518. PMEC-SETS_Milestone_1.1.1_Part1_10302014.pdf.*

## Deliverable 21.3.1: Report outlining strategy for utility interconnect.

NNMREC has 1) identified all the relevant utilities, has 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.

### Related Publications

Pacific Energy Ventures. (2013). PMEC Interconnection Strategy. *Confidential document uploaded to MHKDR. The document will be publicly available in July 2018.*

# Northwest National Marine Renewable Energy Center (NNMREC)

**Appendix J: Deliverables for Task 22:** ***Critical Infrastructure***

***Subtasks 22.1 Monitoring Instrumentation Payload System; 22.2 Grid Emulation; 22.3 Anchoring and Mooring; 22.4 Composite Cables***

**DOE Award Number: DE-FG36-08GO18179-M001**

**Period Covered: 9/15/2008 – 3/14/2016**

**Delivered: June 30, 2016**

**Oregon State University**

**University of Washington**

## Deliverables



## Deliverable 22.1.1: Prototype instrumentation payload system

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) 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 and AMP, progressing from tank testing to open water deployment.

A SeaEye Falcon ROV was modified with additional thrusters, cameras, and linear actuators to deploy an integrated instrumentation package (AMP) to a cabled docking station on the seabed. The drag coefficients of the ROV and AMP were characterized through simulation and validated through free-decay pendulum testing. Results suggest that deployment should be possible in currents up to 0.7 m/s, provided that a launch system is used to minimize the umbilical drag that must be overcome by the ROV thrusters. In field testing, deployment in 15 m depth required currents < 0.5 m/s for effective maneuverability due to umbilical drag. The combined system provided the backbone infrastructure for further instrumentation package development under separate support from DOE and DOD (NAVFAC). The securement system to latch the AMP to its docking station is novel and may have applications elsewhere in marine energy or ocean engineering.

The ability of an inspection-class ROV to deploy a relatively large integrated instrumentation package was successfully demonstrated. 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.

### Related Publications

Joslin J., B. Polagye, A. Stewart, B. Fabien B. Dynamic simulation of a remotely-operated underwater vehicle in turbulent currents for marine energy applications. *In revision.*

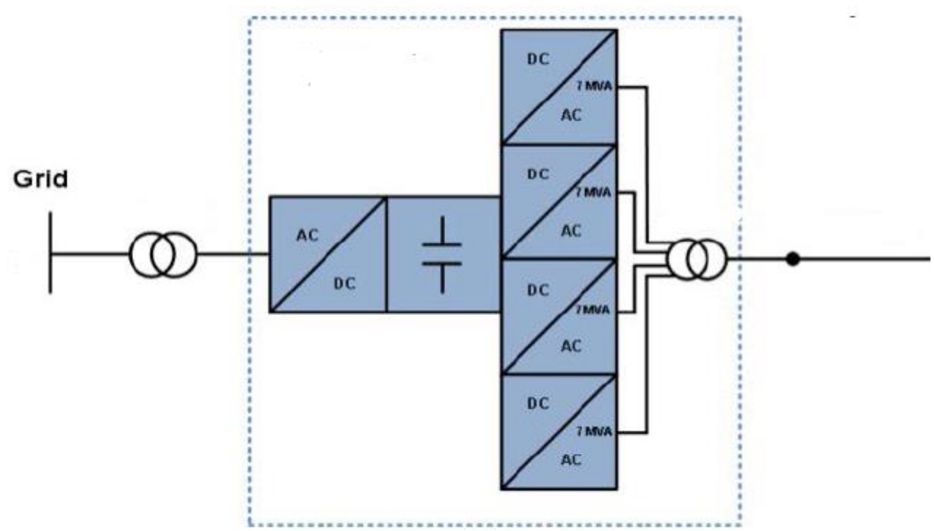
Joslin J., B. Polagye, A. Stewart. Hydrodynamic coefficient determination for an open-framed underwater vehicle. *In revision.*

Joslin J., B. Polagye, B. Rush, A. Stewart. (2014). Development of an Adaptable Monitoring Package for marine renewable energy projects, Part II: Hydrodynamic performance. *2nd Marine Energy Technology Symposium*. Seattle, WA. http://www.globalmarinerenewable.com/images/pdf/METS_PAPERS_VII/110-Joslin.pdf

Rush B., J. Joslin, A. Stewart, B. Polagye. (2014). Development of an Adaptable Monitoring Package for marine renewable energy projects, Part I: Conceptual design and operation. *2nd Marine Energy Technology Symposium*. Seattle, WA. https://depts.washington.edu/nnmrec/docs/METS_AMP_Part1_REV1.1.pdf

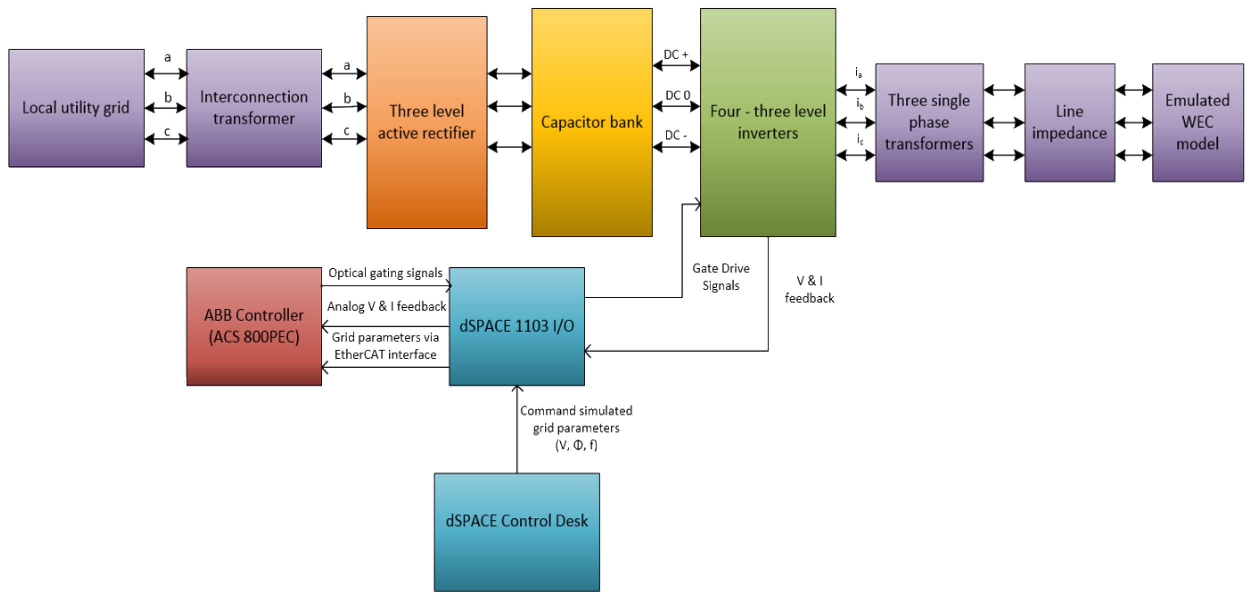
## Deliverable 22.2.1: Pre-design for grid emulator

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).




*Grid Emulator topology.*

Existing technologies have been investigated, and models/simulations have been 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 below.




*Planned Grid Emulator hardware-in-the-loop set-up in WESRF.*

For the hardware validation, the researchers were planning 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 Controllable Grid Interface 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.

## NNMREC Grid Emulator Development White Paper

The Northwest National Marine Renewable Energy Center (NNMREC) is in the process of developing a design specification for a grid emulator for the testing of full-scale Wave Energy Converters (WECs). All of NNMREC's marine energy converter testing facilities are being branded as the Pacific Marine Energy Center (PMEC), including the scaled lab testing facilities and intermediate and full-scale open water testing facilities. This grid emulator would be installed at the onshore location of the PMEC South Energy Test Site (PMEC-SETS); the first proposed utility scale, cable-to-shore, grid-connected wave energy test site in the US, ranging in depth from 60-70 meters, with up to four test berths, 5-6 miles from shore for testing individual WECs or arrays.

## Capabilities

Grid emulator capabilities at a cable-to-shore test facility enable the WEC developer to test synchronization and power delivery to a conventional power grid and would allow for characterization of the WEC electrical generator performance, power quality verification and fault testing before a device is directly connected to the actual power grid. These capabilities are important to the local utility to ensure the testing of experimental WECs does not negatively impact other customers on the distribution line hosting the PMEC-SETS facility.

From client testing objectives learned from the wind energy, characterization tests of interest may include, but are not limited to the following:

- Power Performance
- Voltage fluctuations: continuous operations and switching
- Current harmonics, inter-harmonics, higher frequency components
- Response to balanced and unbalanced low- and high- voltage faults
- Active Power: maximum measurement, ramp rate limitation, set point control, inertial response
- Reactive Power: Reactive power capability, set point control
- Grid protection
- Reconnection time

Optimally, switchgear at the shore facility will allow either a single device (or cable) from the SETS to connect with the grid emulator, or multiple cables for array testing (within the designed power limits of the grid emulator).

## Development Process

NNMREC is evaluating the current WEC developer market to anticipate needs and potential first customers of a grid emulator at the PMEC-SETS. The National Renewable Energy Laboratory (NREL) is also participating in an advisory role, yielding knowledge they gained in going through a similar process in the development of the Controllable Grid Interface (CGI) at their National Wind Technology Center.

In addition to determining needs and requirements, graduate research assistants participating in the project are also developing MATLAB Simulink models for performing computer simulations of a grid emulator, which can be modeled to accurately represent the system interfacing with various WEC devices. Low power hardware verification of these models may also be performed in the Wallace Energy Systems and Renewables Facility.

Once the funding timeline is known, a stakeholders group will be assembled to include any interested parties in finalizing the grid emulator system specification. This could include device developers, potential grid emulator suppliers, representatives from the local utility, regulators, funding source representatives, etc.

Following the development of a detailed grid emulator system specification as part of this current project, the system can be put out for bid when adequate funding is in place. Aligning the grid emulator power and voltage ratings with the cable design at the SETS, the local power grid ratings, and prospective WECs to be tested, puts a preliminary specification with an input power rating of 3-5 MW and grid voltage of 12.47 kV.

Currently, only ABB has an existing product line for a grid emulator at this high power level. Their product was developed with NREL in designing NREL's CGI and allows for 6.3 MW of continuous power with short-circuit and asymmetric fault capabilities. Cost of a similar system at the PMEC-SETS would be approximately $3M for the grid emulator and support systems. Reduced functionality is available at lower cost, e.g., no fault testing capabilities; this study will determine if those options are viable for WEC testing. This difference involves changing the WEC interface of the ABB grid emulator from four parallel 6.3 MW inverters allowing fault testing, to a single 6.3 MW inverter allowing only symmetrical testing; this change includes a different input transformer as well. The cost of the system for symmetrical testing would be approximately $2M. Additionally, the ABB system is modular, allowing for future expansion; entire systems can be run in parallel for higher power capacity, or inverter modules and the input transformer can be changed out to allow fault testing at a later date.

The acquisition timeline is also critical to be in alignment with the PMEC-SETS developments, taking into account the grid emulator bid process, awarding, contracting, final design and build, testing, shipping, commissioning, etc. The goals of this grid emulator overview include both updating stakeholders on the project process and to inquire on the estimated grid emulator funding timeline, e.g., considering the $3M cost estimate.

### Related Publications

Biligiri K. (2014). Grid Emulator for Wave Energy Converter Testing. Master's thesis, Oregon State University. http://hdl.handle.net/1957/52359

Biligiri K., S. Harpool, A. von Jouanne, E. Amon, T. Brekken. (2014). Grid Emulator for Compliance Testing of Wave Energy Converters. *SusTech 2014*.

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.* Washington DC. http://www.nationalhydroconference.com/index/post-show/2015-mets-presentations.html

## Deliverable 22.3.1: Dynamic model for slack moored WECs

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 Mr. Baker, a former MS student on the project (see Baker et al. 2014a & b, 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 by Mr. Lou in 2016. Systematic design procedures for WEC devices including mooring system were developed (Bosma et al. 2012 and 2013).

## Related Publications

Baker J. (2013). Mooring analysis of the Ocean Sentinel through field observation and numerical simulation. Master's thesis, Oregon State University. http://hdl.handle.net/1957/44737

Baker J., S.C. Yim, E. Amon, S. Moran, T. Lettenmaier, A. von Jouanne. (2014). Mooring Analysis of a NOMAD Buoy through Experimental Testing and Numerical Simulation. *33rd International Conference on Ocean,* Offshore *Mechanics and Arctic Engineering Conference*. San Francisco, CA. http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=25AAC13E52BDBB6ECED6CFFE5812D855?doi=10.1.1.657.2267&rep=rep1&type=pdf

Baker J., S.C. Yim, E. Amon, S. Moran, T. Lettenmaier, A. von Jouanne. (2014). Numerical and Experimental Analysis of the Ocean Sentinel Instrumentation Buoy Mooring System to Enable Improved Modeling and Design. *2nd Marine Energy Technology Conference*. Seattle, WA. http://vtechworks.lib.vt.edu/handle/10919/49234

Bosma B., T. Brekken, H.T. Ozkan-Haller, S.C. Yim. (2013). Wave Energy Converter Modeling in the Time Domain: A Design Guide. *1st IEE Conference on Technologies for Sustainability*. Portland, OR. Paper No. SusTech2013-1569746933.

Bosma B., Z. Zhang, T. Brekken, H.T. Ozkan-Haller, C. McNatt, S.C. Yim. (2012). Wave Energy Converter Modeling in the Frequency Domain: A Design Guide. *IEEE Energy Conversion Congress and Exposition*. Raleigh, NC. pp.2099-2106.

Lou J. PhD thesis (to be published). Oregon State University.

von Jouanne A., J. Baker, S.C. Yim, E. Amon, S. Moran, T. Lettenmaier, M. Bunn, A. Yokochi. (2014). Wave Energy Research, Development and Testing Including Testing of Materials and Technology for Bio-Fouling and Corrosion Prevention. *Offshore Technology Conference*. Houston, TX.

## Deliverable 22.4.1: Research Report on composite mono-cables

A report was produced under this subtask that resulted in a published paper. This paper presents the analysis and design of single point power-mooring cables applied to wave energy converters (WECs). A mooring cable design process is suggested, and effects of cable cross-sectional layout, material selection, and conductor design on cable properties are investigated. The study focuses on cable design and structural material for a long service life. Six designs and four structural materials were studied for a total of 18 different configurations. The materials used for the study included Vectran HS, Kevlar 49, Carbon fibers in a vinyl ester matrix, and MP35N alloy. Cable design had minimal impact on cable properties. Material used and component helical angle exhibited significant impact on cable mechanical properties. Synthetic fiber designs exhibited more desirable mechanical properties and fatigue performance than both carbon fibers in a vinyl ester matrix and MP35N alloy. Wave device heave and cable tension were not affected by cable material.

## Related Publications

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