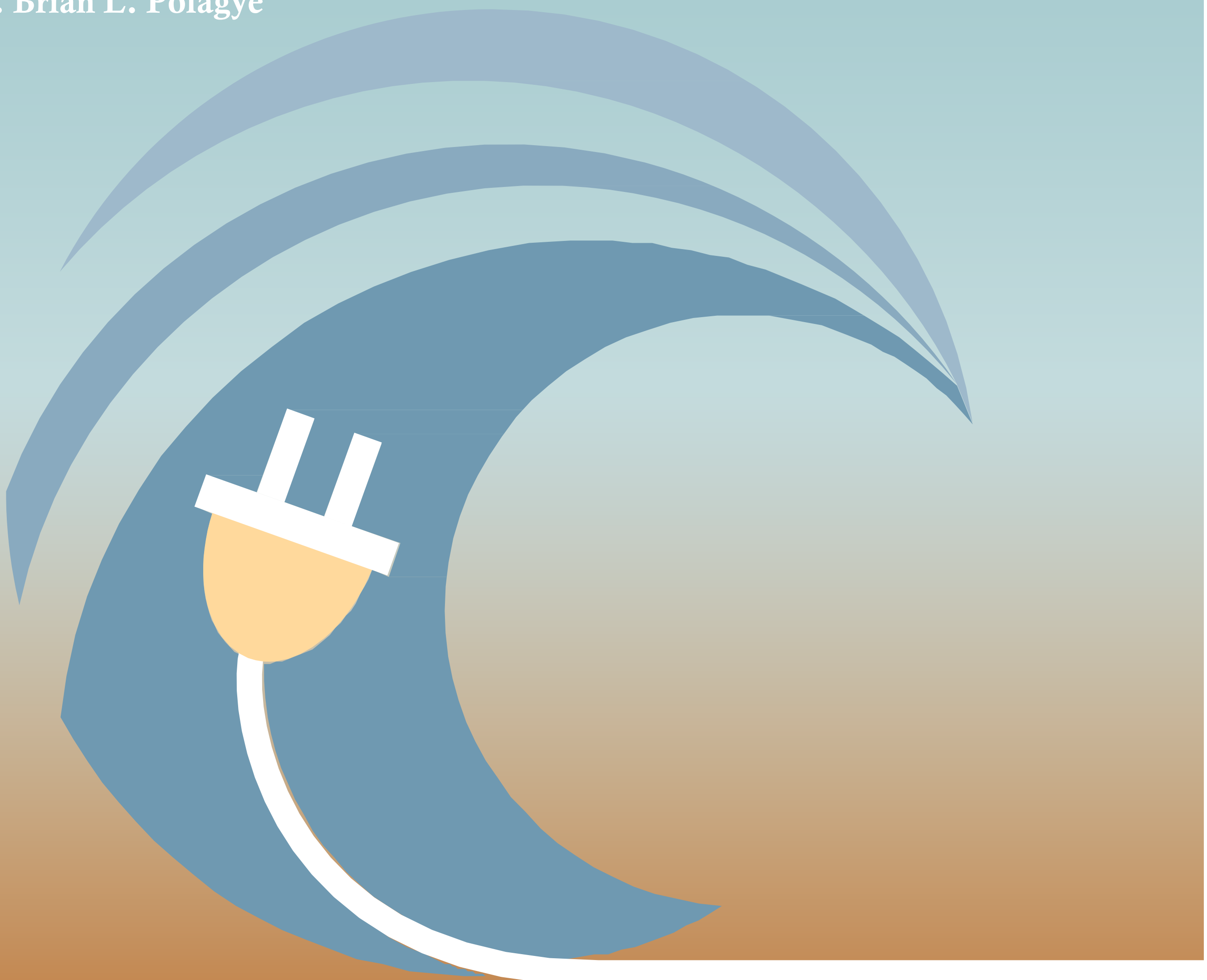
Northwest National Marine Renewable Energy Center

Report #5
May 2013

NNMREC Accomplishments and Impacts 2009-2013

Dr. Belinda Batten
Dr. Brian L. Polagye



UNIVERSITY of WASHINGTON

Oregon State UNIVERSITY

Oregon State University

Belinda Batten
Director
541-737-9492
belinda.batten@oregonstate.edu

Brenda Langley
Program Manager
541-737-6138
brenda.langley@oregonstate.edu

nnmrec.oregonstate.edu

University of Washington

Brian L. Polagye
Co-Director
206-543-7544
bpolagye@uw.edu

depts.washington.edu/nnmrec

Suggested Citation: Batten, B. and B. L. Polagye. 2013. NNMREC Accomplishments and Impacts 2009-2013 . NNMREC Report #5. Corvallis: NNMREC. 55 pp.

Partial funding for this material was provided by U.S. Department of Energy and the Oregon Wave Energy Trust (OWET).

OWET is funded in part with Oregon State Lottery Funds administered by the Oregon Business Development Department. It is one of six Oregon Innovation Council initiatives supporting job creation and long-term economic growth.

CONTENTS

ACKNOWLEDGMENTS 3

INTRODUCTION 4

NNMREC PERSONNEL 5

RESEARCH ACCOMPLISHMENTS 6

Advanced Wave Forecasting Technologies 6

Accomplishments 6

Publications 8

Device and Array Optimization – Wave Energy 9

Accomplishments 9

Publications 12

Device and Array Optimization – Tidal Energy 14

Accomplishments 14

Publications 15

Integrated and Standardized Test Facility Development – Wave Energy 17

Accomplishments 17

Publications 20

Integrated and Standardized Test Facility Development – Tidal energy 21

Accomplishments 21

Publications 22

Investigate Compatibility of Marine Energy Technologies with Environment, Fisheries and other Marine Resources 24

Accomplishments 24

Publications 27

Increased Reliability and Survivability of Marine Energy Systems – Wave Energy 29

Accomplishments 29

Publications 31

Increased Reliability and Survivability of Marine Energy Systems – Tidal Energy 32

Accomplishments 32
Publications 32
Collaboration/Optimization with Marine Renewable and Other Renewable Energy Resources 33
Accomplishments 33
Publications 34
Pacific Marine Energy Center 35
Accomplishments 35
Publications 36
Overview Publications 36
Technical Presentations 37
OUTREACH AND ENGAGEMENT 43
Outreach and Engagement Presentations 45
LESSONS LEARNED 48
PATENTS 50
REFERENCE MODEL EFFORT 50
EDUCATING THE WORKFORCE 51
Graduated Students 51
Current Students 52
COLLABORATIONS 54

ACKNOWLEDGMENTS

The authors acknowledge that this document represents the work of many faculty and graduate students who are listed within. Further, this work would not have been possible without the generous support of the US Department of Energy, the Oregon Wave Energy Trust, Bureau of Ocean Energy Management, Snohomish Public Utility District, Oregon State University, the University of Washington, Oregon BEST, Oregon Department of Energy, State of Oregon, National Science Foundation, the Flora Family Foundation and the Seattle Foundation.

We also acknowledge the contributions from our partners and collaborators. The primary partners in our effort thus far include: Aquatera, AXYS, Ecology and Environment Inc, the European Marine Energy Center, the fishermen of FINE, ICF International, National Renewable Energy Laboratory, NRC Environmental, numerous organizations and departments at Oregon State University and University of Washington, Oregon Wave Energy Trust, Pacific Energy Ventures, Pacific Northwest National Laboratory, Port of Newport, Port of Toledo, SAIC, Sandia National Laboratory, SMI/Helios Strategies, Sound & Sea Technology, Sea Mammal Research Unit, 3U Technologies, Wiggins Tug and Barge, the multitude of device developers, and the numerous regulatory and resource agency representatives who work to make our testing program possible.

Lastly, the authors thank Sammantha Payment and Brenda Langley for their outstanding assistance in preparing this report.

The material in this report is based upon work supported by the Department of Energy under Award Number DE-FG36-08GO18179.

INTRODUCTION

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

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

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

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

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

This report contains an overview of significant accomplishments, current work and publications produced under each of these tasks, as well as lessons learned and NNMREC's impact. Impact is being reported in terms of presentations given, graduated and current students, collaborations and patents.

NNMREC PERSONNEL

Faculty/Staff Member	Area/University	Specialization
Roberto Albertani	Mechanical Engineering, OSU	Composites, Off-shore Wind Energy
Alberto Aliseda	Mechanical Engineering, UW	Hydrodynamics: Experimental and Computational
Ean Amon	Electrical Engineering, OSU	Power Systems; Test Engineer
Belinda Batten	Mechanical Engineering, OSU	Modeling and Control of Devices and Arrays
George Boehlert	Hatfield Marine Science Center, OSU*	Environmental Research Director (2008-2012)
Ted Brekken	Electrical Engineering, OSU	Modeling and Control of Devices and Arrays; Power Systems
Flaxen Conway	Marine Resource Management, OSU	Communication Engagement, Human Dimensions Research
Brian Fabien	Mechanical Engineering, UW	Dynamics and Control: Mooring System Analysis
Merrick Haller	Civil Engineering, OSU	Wave Resource Characterization; Scaled Testing; Device and Array Effects
Joe Haxel	Hatfield Marine Science Center, OSU	Passive Acoustic Modeling, Analysis and Testing
Sarah Henkel	Hatfield Marine Science Center	Benthic Ecology, Environmental Research Director (2013-present)
Kaety Hildenbrand	Oregon SeaGrant	Community Engagement, Fisheries Specialist
John Horne	Fisheries and Aquatic Sciences, UW	Pelagic Fisheries; Environmental Effect Frameworks
Mitsuhiro Kawase	Oceanography, UW	Effects of Energy Removal from Estuarine Ecosystems
Brenda Langley	NNMREC, OSU	Program Representative
Phil Malte	Mechanical Engineering, UW	Modeling and Control of Devices and Arrays
Sean Moran	NNMREC, OSU	Ocean Test Facilities Manager
Michael Motley	Civil Engineering, UW	Fluid-structure Interactions for Turbine Blades
Tuba Ozkan- Haller	Oceanography, OSU	Wave Resource Characterization; Scaled Testing; Device and Array Effects
Robert Paasch	Mechanical Engineering, OSU	Device and PTO Design, Reliability and Survivability
Brian Polagye	Mechanical Engineering, UW	Tidal Resource Characterization, Environmental Effects, Device Optimization
Jim Riley	Mechanical Engineering, UW	High-resolution Oceanographic Simulation
Adam Schultz	Oceanography, OSU	Electro-magnetic Field Modeling, Analysis, Testing
Rob Suryan	Hatfield Marine Science Center, OSU	Seabird Ecologist
Jim Thomson	Civil Engineering and Applied Physics Laboratory, UW	Hydrodynamic Measurements, Instrumentation Platform Development
Mark Tuttle	Mechanical Engineering, UW	Durability of Composite Materials
Annette von Jouanne	Electrical Engineering, OSU	Power Systems, Device Design, MOTB team leader
Solomon Yim	Civil Engineering, OSU	Computational Fluid-Structure Interaction Modeling
Alex Yokochi	Chemical Engineering, OSU	Biofouling; Reliability and Survivability of Materials

*retired

RESEARCH ACCOMPLISHMENTS

ADVANCED WAVE FORECASTING TECHNOLOGIES

ACCOMPLISHMENTS

A major roadblock in the integration of power from wave energy converters (WECs) into the electrical grid is the temporally variable nature of the extracted power, requiring other forms of (potentially expensive) power to balance the load. NNMREC research has addressed this roadblock in two ways. First, the predictability of the wave resource is a major advantage over other renewable energy resources such as terrestrial wind. However, high-resolution nearshore predictions of the wave field off the coast of Oregon did not exist before NNMREC. Ozkan-Haller's research has been geared toward remedying this shortcoming and achieved a state where 84-hour high-quality and validated forecasts are now available (see Figure 1). The extensive data case we are building with the forecasts is also helpful for further localized resource characterization for developers who are looking at specific locations as potential deployment sites.

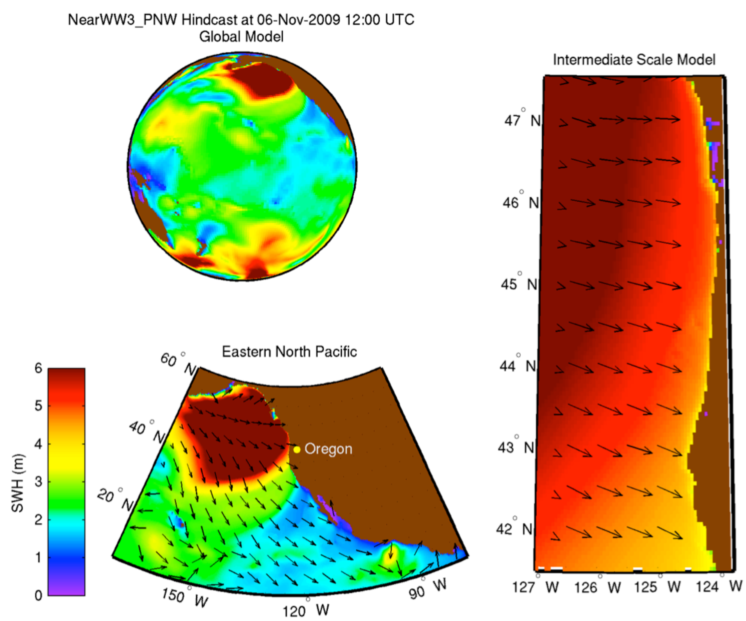


Figure 1: The global (top left), Eastern North Pacific (bottom left) domains that are identical to those used by the National Center for Environmental Prediction, and the local Oregon domain (right panel). The grids covering the domains have increasing resolution, resulting in predictions over 600 –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

A second way to address the issue of the variable nature of the extracted power is to analyze the effect of large array installments on the resulting power output. Cross-disciplinary collaboration between Ozkan-Haller and Brekken resulted in a study where they analyzed the power generated by 400 devices in a realistic wave field and found that the combined power output from the array was quite stable, suggesting another solution to the stable power requirement.

Wave-WEC interactions heavily influence the power extracted from waves as well as the changes to the wave field in the lee of a device. Complex wave-structure interaction models exist that can account for the interplay between the waves and the structures; however, these models can be exceedingly computationally intensive, and their use is not feasible for utility scale arrays. Therefore, parameterizations of the wave-WEC interaction processes are needed. Ozkan-Haller, Haller and Brekken have spent significant effort to develop such parameterizations. Their results indeed indicate that regional-scale wave propagation models can be modified to account for the wave-structure interaction effects. They have also outlined the general limits to their applicability.

A third area of investigation has involved the estimation of far-field effects due to the presence of an array of WECs. In particular, the interest has been in the effect of the devices on the wave field in their lee, and the potential effect of such modifications on neighboring beaches. One important finding of this work has been related to two different kinds of devices. When comparing near-resonant devices and wave-following devices that extract the same amount of energy, they found that the near-resonant devices scatter more wave energy compared to the wave-following devices and, therefore, induce a much larger far-field effect in the lee of the devices. Note that the compared devices extracted identical amounts of energy from the wave field. This finding still needs to be verified experimentally, and, once verified, points toward a direction of development for devices that might reconcile the desire for maximum power output and minimal environmental impact.

Haller's group supported the development of the wave climatology for the Newport North Energy Test Site (NETS) by generating a monthly wave climatology database through a linear wave transformation analysis based on available historical data. During the first half of the base grant time period, this database was utilized by developers to plan for deployments with the Ocean Sentinel. This climatology has subsequently been supplanted by a comprehensive hindcast analysis based on WAVEWATCH with Ozkan-Haller and others during the second half of the base grant time period. Additionally, a high-resolution SWAN model hindcast for 2010-2011 for the Newport nearshore area was produced. This hindcast was performed at higher resolution than the aforementioned WAVEWATCH effort, and covers the entire nearshore area to the shorelines. Hence, the WAVEWATCH and SWAN efforts are complementary. A short-term deployment of a WaveRider wave buoy was also conducted during Aug 2010 - June 2011 for model/data verification.

Current work in the task is focused on two thrusts. First a high-resolution wave hindcast is being used to extend the wave resource characterization work that had so far been carried out only with isolated wave buoy records. This work will result in a comprehensive wave resource characterization that will also complement the DOE-funded characterization work. The wave forecasting work that feeds into this activity is continuing with published daily forecasts that are made available to the general public through the Northwest Association of Networked Ocean Observing Systems (see http://nvs.nanoos.org/). More specific requested information is also made available to Oregon Wave Energy Trust (OWET)-funded efforts to more generally understand projected power output from devices.

Second, NNMREC researchers are further investigating array designs that will minimize wave field modification while also maximizing the stable power that can be obtained by the array. These considerations will increase the likelihood of arrays that can be readily integrated into the electrical grid with minimal environmental impact; thus this work overlaps the work in optimizing arrays, and investigating environmental effects.

PUBLICATIONS

1. G. Garcia-Medina, H. T. Özkan-Haller, P. Ruggiero, and J. A. Oskamp, Wave prediction system for the US Pacific Northwest, *Weather and Forecasting*, 2013.
2. T.K.A. Brekken, T. Özkan-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.
3. S. Kassem, and H. T. Özkan-Haller, Forecasting the wave-current interactions at the mouth of the Columbia River, OR, USA. *Proceedings of the 33rd International Conference on Coastal Engineering*, Santander, Spain, 2012.
4. G. García-Medina, H. T. Özkan-Haller, and P. Ruggiero, Nearshore wave predictions along the Oregon and southwest Washington coast. *Proceedings of the 33rd International Conference on Coastal Engineering*, Santander, Spain, 2012.
5. J. Oskamp, and H. T. Özkan-Haller, Wave predictions at the site of a wave energy conversion array. *Proceedings of the 32nd International Conference on Coastal Engineering*, Shanghai, China, 2010.

DEVICE AND ARRAY OPTIMIZATION – WAVE ENERGY

ACCOMPLISHMENTS

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

A key component in bringing ocean wave energy converters from concept to commercialization is to design, build and test scaled prototypes to provide model validation. Two efforts have been undertaken along these lines at OSU.

In the first project, two PhD students, Lewis and Bosma, have worked with their faculty advisors, von Jouanne and Brekken on the development of an Autonomous Wave Energy Converter (AWEC), for low power autonomous and remote applications (200 W continuous). A one-quarter scale prototype of an autonomous two-body heaving point absorber was designed, built and tested; the design is shown in Figure 2. Specifically they tested the AWEC on the wave energy linear test bed in the Wallace Energy Systems and Renewables Facility (WESRF) (see Figure 3), and in OSU swimming pools. These pool tests were to optimize the buoyancy in preparing for wave tank testing in the O. H. Hinsdale Wave Research Lab's Large Wave Flume, see Figure 4.

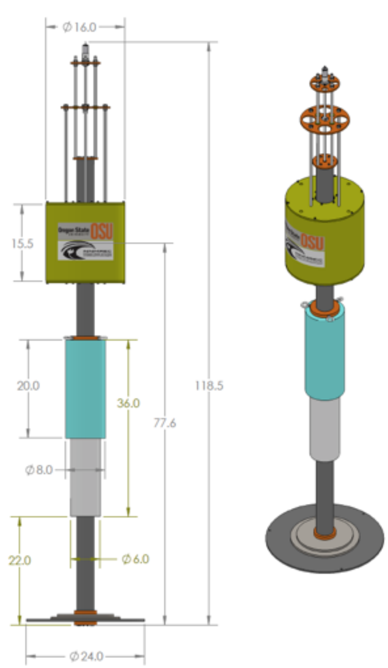


Figure 2: AWEC Design Concept

Figure 3: AWEC Testing on the Wave Energy Linear Test Bed in WESRF

Power produced during wave tank testing is shown in Figure 5. This work will serve as a guide for future developers of WECs, providing insight to the process involved in taking their concept to prototype stage.

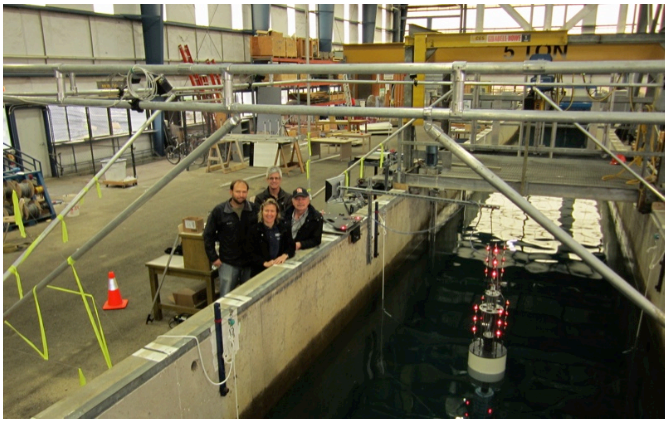


Figure 4: AWEC Testing in Hinsdale's Large Wave Flume

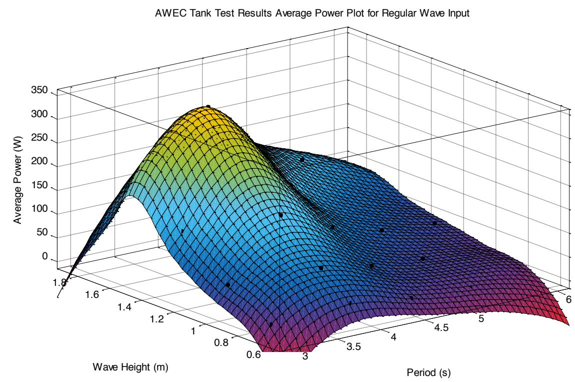


Figure 5: Power Produced by AWEC in Tank Testing

Boren, a master's student in Mechanical Engineering, modeled a horizontal pendulum wave energy converter (PWEC) for use in a variety of control methodology studies; see Figure 6. Specifically, under cost match funding, Boren developed a dynamic model for a PWEC, and compared controlled and uncontrolled performance in irregular sea states. This work has been submitted to the European Wave and Tidal Energy Conference and will be presented in Aalborg Denmark in September 2013.

Boren also advised two senior projects, one to produce the power take off pendulum-gear box system, and the other to produce a composite hull to house the power take off. Together, these two senior projects provide a platform that all NNMREC faculty and students can use to advance other research projects in control design and testing. This work contributes to the reliability and survivability task as well, as all PWEC components are secured within a protective hull. In this way, the destructive and corrosive nature of the ocean is better constrained and greater WEC component longevity is predicted.

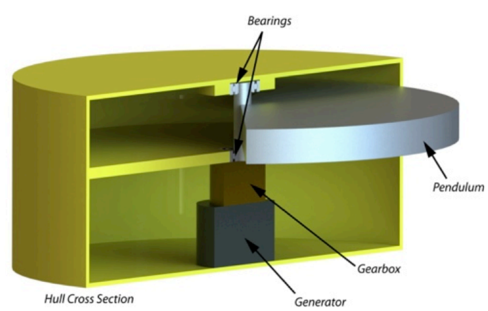


Figure 6: Pendulum Wave Energy Converter

At a more "general" level, Brekken and Bosma have focused on creating a testing guide for developers. This guide is meant to provide basic instruction and examples in WEC modeling and performance estimation in four main areas: frequency domain analysis, time-domain and frequency-domain hybrid analysis, fully non-linear time-domain analysis, and hardware tank testing.

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

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

As the ocean wave energy field continues to mature, developers need a generic modeling methodology to test their designs before building prototypes. To address this need, a design methodology for a first pass time domain simulation is the next step. Built on results from the frequency domain analysis, the general procedure for obtaining time domain results is presented. Specifically, a methodology for modeling a two-body point absorber WEC in the time domain was outlined. The procedure included defining equations of motion and implementing them in a differential equation solver such as MATLAB/Simulink. A benefit of time domain simulation, namely the implementation of a nonlinear damping power take off model, was demonstrated.

While this project was not initially planned at NNMREC's founding, Brekken recognized early in the funding period that a product of this type was needed. This guide provides a way to disseminate the modeling work, as well as a structure to guide future modeling work.

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 regarding the environmental effects of WEC-arrays. Extensive effort went into verifying the parameterization using the lab data and through model/model comparisons in collaboration with the Ozkan-Haller group. It is the first WEC-array parameterization, appropriate at field scales, that is based on actual WEC-array performance (as opposed to idealized performance). Original project plans included collecting remote sensing observations of devices under ocean testing. However, since only single devices have been deployed at Newport NETS, and the deployments have only been during the mildest of wave conditions, there has not been a good opportunity for this type of data collection. Hence, more efforts have focused on learning from existing laboratory data.

Current and ongoing tasks involve: 1) a model study of the impact of WEC-arrays on the nearshore wave field at Oregon coastal sites and 2) an analysis of stereo video data for the purpose of quantifying the wave scattering processes in the near-field of a WEC-array.

PUBLICATIONS

1. T. Brekken, and A. von Jouanne, Scaled development of a novel wave energy converter including numerical analysis and high resolution tank testing, *Proceedings of the IEEE Special Issue on "Marine Energy Technology"*, 2013.
2. T. K. A. Brekken, K. Rhinefrank, A. von Jouanne, A. Schacher, J. Prudell, and E. Hammagren, Scaled development of a novel wave energy converter including numerical analysis and high-resolution tank testing, *Proceedings of the IEEE*, vol. 101, no. 4, pp. 866–875, 2013.
3. B. Boren and B. Batten, On the modeling and control of horizontal pendulum wave energy converters, *10th European Wave and Tidal Energy Conference*, Aalborg, Denmark, September 2013, accepted.
4. B. Nair and R. Shendure, Low-cost utility-scale wave energy enabled by magnetostriction, *Marine Energy Technology Symposium (GMREC)*, Washington, DC, 2013.
5. K. Ruehl, B. Paasch, T.K.A. Brekken, and B. Bosma, Wave energy converter design tool for point absorbers with arbitrary device geometry, in *International Ocean and Polar Engineering Conference (ISOPE)*, Anchorage, AK, June-July 2013.
6. C. Stillinger, T.K.A. Brekken, and A. von Jouanne, Furthering the study of real-time life extending control for ocean energy conversion, in *Power and Energy Society General Meeting*, pp. 1–9, 2012.
7. B. Bosma, Z. Zhang, T.K.A. Brekken, T. Ozkan-Haller, C. McNatt, and S. Yim, Wave energy converter modeling in the frequency domain: A design guide, in *Energy Conversion Congress and Exposition (ECCE)*, pp. 2099–2106, 2012.
8. E. Amon, T.K.A. Brekken, and A. Schacher, Maximum power point tracking for ocean wave energy conversion, *IEEE Transactions on Industry Applications*, vol. 48, pp. 1079–1086, May-June 2012.
9. T. Lewis, A. von Jouanne, and T.K.A. Brekken, Modeling and control of a slack-moored two-body wave energy converter with finite element analysis, in *Energy Conversion Congress and Exposition (ECCE)*, pp. 938–945, 2012.
10. M. Richter, M. Magana, O. Sawodny, and T.K.A. Brekken, Nonlinear model predictive control of a point absorber wave energy converter, *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 118–126, 2012.
11. K. Rhinefrank, A. Schacher, J. Prudell, T.K.A. Brekken, C. Stillinger, J. Yen, S. Ernst, A. von Jouanne, E. Amon, R. Paasch, A. Brown, and A. Yokochi, Comparison of direct-drive power takeoff systems for ocean wave energy applications, *IEEE Journal of Oceanic Engineering*, vol. 37, pp. 35–44, January 2012.
12. T. Lewis, A. von Jouanne, and T. Brekken, Modeling and control of a slack-moored two-body wave energy converter with finite element analysis, *ECCE*, Sept. 2012. Prize Top Student Oral Presenter Award.
13. C. Stillinger, T. Brekken, and A. von Jouanne, Furthering the study of real-time life extending control for ocean energy conversion, *PES 2012*, San Diego, CA, July 2012.
14. J. Oskamp, and H. T. Özkan-Haller, Power calculations for a passively tuned point absorber wave energy converter on the Oregon Coast, *Renewable Energy*, 2012.
15. T. Lewis, A. von Jouanne, and T.K.A. Brekken, Per unit wave energy converter system analysis, in *Energy Conversion Congress and Exposition (ECCE)*, Phoenix, AZ, pp. 4123–4129, September 2011.
16. T. Lewis, A. von Jouanne, and T.K.A. Brekken, Wave energy converter with wideband power absorption, in *Energy Conversion Congress and Exposition (ECCE)*, Phoenix, AZ, pp. 3844–3851, September 2011.
17. K. Rhinefrank, A. Schacher, J. Prudell, E. Hammagren, Z. Zhang, C. Stillinger, T.K.A. Brekken, A. von Jouanne, and S. Yim, Development of a novel 1:7 scale energy converter, in *Offshore Mechanics and Arctic Engineering Conference*, Rotterdam, Netherlands, June 2011.
18. T.K.A. Brekken, On model predictive control for a point absorber wave energy converter, in *PowerTech*, Trondheim, Norway, pp. 1–8, June 2011.

19. K. Rhinefrank, A. Schacher, J. Prudell, C. Stillinger, D. Naviaux, T. Brekken, and A. von Jouanne, Numerical analysis and scaled high resolution tank testing of a novel wave energy converter, *Journal of Offshore Mechanics and Arctic Engineering,* 2011.
20. D. Elwood, S. Yim, E. Amon, A. von Jouanne, and T. Brekken, Estimating the energy production capacity of a taught moored, dual body, wave energy conversion system using numerical modeling and physical testing, *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 133, 031102-1 - 031102-9, August 2011.
21. A. von Jouanne and T. Brekken, Wave Energy Research, Development and Demonstration at Oregon State University, *PES 2011*, Detroit, July 2011.
22. D. Elwood, S. Yim, E. Amon, A. von Jouanne, and T.K.A. Brekken, Experimental force characterization and numerical modeling of a taught moored dual body wave energy conversion system, *Journal of Offshore Mechanics and Arctic Engineering*, vol. 132, Feb. 2010.
23. T. Brekken, Fundamentals of ocean wave energy conversion, modeling, and control (tutorial), in *Industrial Electronics (ISIE), 2010 IEEE International Symposium on*, pp. 3921 –3966, 2010.
24. T.K.A. Brekken, H. Hapke, C. Stillinger, and J. Prudell, Machines and drives comparison for low-power renewable energy and oscillating applications, *IEEE Transactions on Energy Conversion*, vol. 25, no. 4, pp. 1162–1170, 2010.
25. J. Prudell, M. Stoddard, E. Amon, T.K.A. Brekken, and A. von Jouanne, A permanent magnet tubular linear generator for ocean wave energy conversion, *IEEE Transactions on Industry Applications*, vol. 46, no. 6, pp. 2392–2400, 2010.
26. K. Ruehl, T. K. Brekken, B. Bosma, and R. Paasch, Large-scale ocean wave energy plant modeling, *in Innovative Technologies for an Efficient and Reliable Electricity Supply (CITRES),* pp. 379 –386, September 2010.
27. D. Elwood, S. Yim, J. Prudell, C. Stillinger, A. von Jouanne, T.K.A. Brekken, A. Brown, and R. Paasch, Design, construction, and ocean testing of a taut-moored dual-body wave energy converter with a linear generator power take-off, *Renewable Energy, An International Journal*, vol. 35, no. 2, pp. 348–354, 2010.
28. K. Rhinefrank, A. Schacher, J. Prudell, T. Brekken, A. von Jouanne, J. Cruz, S. Yim, and D. Cox, Numerical and Experimental Analysis of a Novel Wave Energy Converter, *OMAE*, Shanghai, China, June 2010.
29. A. Brown, R. Paasch, I. Tumer, P. Lenee-Bluhm, J. Hovland, T. Brekken, and A. von Jouanne, Towards a definition and metric for the survivability of ocean wave energy converters, *ASME 2010 International Conference on Energy Sustainability*, May 2010.
30. T. Brekken, A. von Jouanne, A. Yokochi, Ocean Wave Energy Overview and Research at Oregon State University, *Ocean Sciences Meeting*, Poster Session, Portland, Oregon, Feb. 2010.
31. K. Rhinefrank, A. Schacher, J. Prudell, C. Stillinger, D. Naviaux, T, Brekken, and A. von Jouanne, Scaled wave energy device performance evaluation through high resolution wave tank testing, *Oceans 2010*, September 2010.
32. J. Prudell, M. Stoddard, E. Amon, T. Brekken, and A. von Jouanne, A permanent magnet tubular linear generator for ocean wave energy conversion*, IEEE Transactions on Industry Applications*, 2010.
33. E. Amon, T.K.A. Brekken, and A. von Jouanne, A power analysis and data acquisition system for ocean wave energy device testing, in *Proceedings of Applied Power Electronics Conference (APEC)*, Washington, DC, pp. 750–754, February 2009.
34. D. Elwood, S. Yim, A. Schacher, K. Rhinefrank, J. Prudell, E. Amon, T. Brekken, and A. von Jouanne, Numerical modeling and ocean testing of a direct-drive wave energy device utilizing a permanent magnet linear generator for power take-off, in *Proceedings of Offshore Mechanics and Arctic Engineering (OMAE)*, Honolulu, HI, pp. 817–824, June 2009.
35. T.K.A. Brekken, J. Prudell, A. von Jouanne, and M. Stoddard, A novel permanent magnet tubular linear generator for ocean wave energy, in *Proceedings of Energy Conversion Congress and Exposition (ECCE)*, San Jose, CA, pp. 3641–3646, September 2009.
36. E. Amon, A. Schacher, and T.K.A. Brekken, A novel maximum power point tracking algorithm for ocean wave energy devices, in *Proceedings of Energy Conversion Congress and Exposition (ECCE)*, San Jose, CA, pp. 2635–2641, September 2009.

ACCOMPLISHMENTS

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

Aliseda's and Polagye's groups have created a tandem of computational model–scaled experimental model of a cross-flow helical turbine. This generic and openly available design has been fabricated at two scales (0.2 m and 1.0 m height) and tested in a flume and in the field, towed behind an unpowered skiff. The torque and power predicted by the numerical simulations were compared to the experimental results. The comparison shed light over the strengths of each of the methodologies in understanding the dynamics of cross-flow MHK turbines. It also identified the challenges in using some specific results from these studies to design and quantify performance of this type of turbine. This research resulted in the first publications on experimental and high-resolution computational study of helical turbines. The information collected and the analysis published has clarified the influence of solidity ratio and tip speed ratio on cross-flow turbine performance; highlighted the impact of upstream blade wake on downstream blade performance; demonstrated the influence of turbulence on rotor performance; and provided insight into wake structure and propagation. It will allow industrial and academic partners to optimize designs of helical cross-flow turbines and it will guide the study, both through scaled-down experiments and through computation, of the resulting prototypes. In addition, the field-scale prototype could serve as a platform for instrumentation development (e.g., testing of fiber optic strain gauges) and technology advancement (e.g., use of Doppler sonars for feedforward control).

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

Fabien's group is focusing on the development of efficient methods to determine the equilibrium configuration of slack moored tidal turbines. Slack mooring provides a cost effective approach to securing tidal turbines in deep water in a manner that combines the positioning flexibility of rigid, pile-mounted foundations and ease of deployment for gravity foundations. In the models developed by NNMREC the submerged body and mooring lines are subject to various loads including: gravity, buoyancy, viscous drag due to a constant stream flow, applied forces and applied torques. The elastic mooring lines in the system can only support tensile loads, and are arranged in a network so that some mooring lines may be completely slack. Here they use a Lagrangian mechanics framework to determine the equations of equilibrium of the system. The models and computer codes developed by Fabien and his team provide capabilities that are not available in commercial codes such as OrcaFLEX. In particular, they are developing strategies for the optimal placement of mooring lines in the system. The mooring line placement algorithms ensure stable operation over a range of stream flow conditions while minimizing the overall cost of the system.

Fabien's team is currently extending these models to accommodate a network of tidal and wave energy devices. The new model developments consider both the static and dynamic behavior of the system. Moreover, feedback control techniques are employed to improve the robustness of the stability condition, and enhance the energy output of the system. In addition, field experiments are being conducted to validate the modeling techniques and control strategies.

A significant accomplishment under the current funding pertained to the effect of turbine depth on device performance in sheared flow, done by Kawase, Fabien and an undergraduate research assistant. Current measurements were taken at various sites in Admiralty Inlet, Washington to investigate how the power harvested by a hypothetical horizontal-axis turbine would depend on the height above bottom at which the turbine is placed, and how that would scale vis-à-vis the cost of the device. The main finding in this work is that, while power in the tidal current increases with height above bottom (z), the increase typically scales as $z^{\sim 0.6}$, which is much less than the scaling of the foundation cost which is expected to be at least proportional to z on the basis of materials cost alone. Thus, it would not be economically beneficial to place a device high in the water column in order to exploit the higher current / power**,** unless a moorings with lower cost scaling, such as the compliant moorings being investigated by Fabien's group, can be developed.

PUBLICATIONS

1. B. Polagye, R. Cavagnaro, and A. Niblick, Micropower from tidal turbines, *ASME 2013 Fluids Engineering Division Summer Meeting*, Incline Village, NV, July 7-11, 2013.

2. B. Polagye, R. Cavagnaro, A. Niblick, T. Hall, J. Thomson, and A. Aliseda, Cross-flow turbine performance and wake characterization, *Proceedings of the 1st Marine Energy Technology Symposium, GMREC-METS13*, Washington, DC, 2013.
3. D. Sale, A. Aliseda, M.R. Motley, and Y. Li, Structural optimization of composite blades for wind and hydrokinetic turbines, Proceedings of the *1st Marine Energy Technology Symposium, GMREC-METS13*, Washington, D.C. April 10-11, 2013.
4. B. Polagye, R. Cavagnaro, A. Niblick, T. Hall, J. Thomson, and A. Aliseda, Cross-flow turbine performance and wake characterization, *Proceedings of the 1st Marine Energy Technology Symposium, GMREC-METS13*, Washington, D.C. April 10-11, 2013.
5. T. A. Javaherchi, N. Stelzenmuller, and A. Aliseda, Experimental and numerical analysis of the DOE Reference Model 1 horizontal axis hydrokinetic turbine, *Proceedings of the 1st Marine Energy Technology Symposium, GMREC-METS13*, Washington, D.C. April 10-11, 2013.
6. T. J. Hall, A. Niblick, B. Polagye, and A. Aliseda, Detailed hydrodynamics of a Cross-Flow Marine Hydrokinetic Turbine: comparison of high resolution computational fluid dynamics and experiments, submitted to *Renewable Energy*, 2013.
7. T. Javaherchi, and A. Aliseda, Calibration of Discrete Random Walk (DRW) Model via G.I. Taylor Dispersion Theory submitted to *Journal of Fluids Engineering*, 2013.
8. B. C. Fabien, Equilibrium of submerged bodies with slack mooring, *Nonlinear Approaches in Engineering Applications*, L. Dai and R. L. Jazar, (Eds.) Springer-Verlag, 2012.
9. T. Javaherchi, and A. Aliseda, Numerical methodology development for the study of the flow field of a Horizontal Axis Wind Turbine, submitted to *Journal of Wind Engineering and Industrial Aerodynamics*, 2012.
10. S. Harding, J. Thomson, B. Polagye, M. Richmond, V. Durgesh, and I. Bryden, Extreme value analysis of tidal stream velocity perturbations, *European Wave and Tidal Energy Conference*, 2011.
11. M. Kawase, P. Beba and B.C. Fabien, Finding an optimal placement depth for a tidal in-stream energy conversion device in an energetic, baroclinic tidal channel, Technical Report, Northwest National Marine Renewable Center, University of Washington, 29pp., 2011.

ACCOMPLISHMENTS

Ocean Testing

A significant part of NNMREC's mission is to facilitate the commercialization of marine energy technologies. To fulfill this mission aspect NNMREC has as one of its objectives, to develop ocean test facilities that can be used by WEC developers to test their prototypes. One of NNMREC's major accomplishments, supported by the initial round of DOE funding, congressionally directed projects, state funding and other non-federal funding cost match, is the permitted North Energy Test Site (NETS) located three miles offshore, in Newport, OR. Another significant accomplishment, supported by the same funding sources, was the design and construction of the mobile ocean test berth, the Ocean Sentinel instrumentation buoy, for use at that test site. The Ocean Sentinel, shown in Figure 7, was completed in 2012 and is based on a NOAA NOMAD buoy platform; it facilitates open-ocean, stand-alone testing of WECs with average power outputs of up to 100 kW.

Figure 7: NNMREC Mobile Ocean Test Berth Instrumentation Buoy (Ocean Sentinel) with Team of Annette von Jouanne, Ean Amon, Terry Lettenmaier, and Sean Moran

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

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

The Ocean Sentinel performed as designed throughout its first deployment, and the ability of the power converter together with the CompactRIO control and data acquisition to control the WET-NZ generator load and collect data proved to be very effective for evaluating WEC performance. The design and development of the Ocean Sentinel and the results of the WET-NZ testing are presented in two Marine Technology Society journal papers in 2013.

As background on the design, development and deployment process for the Ocean Sentinel, the NOMAD hull was delivered to the Toledo Boatyard, just upriver from Newport. NNMREC integrated into the Ocean

Sentinel the switch gear, converter, load banks and telemetry system, as well as the mounting structures for the umbilical cable. The WET-NZ device arrived at the Toledo Boatyard, followed by system integration with its Power Pod power take off and commissioning of the systems. This work included collaboration with NREL and the integration of their instrumentation modules.

The Ocean Sentinel anchors/moorings were deployed along with the corner marker buoys in mid-August. The Ocean Sentinel was then towed from the Toledo Boatyard to Newport Ship Operations at the pier near the Hatfield Marine Science Center. The Ocean Sentinel along with the TRIAXYS wave monitoring buoy (shown in Figure 8) which measures wave magnitude, period, direction, and currents, were deployed using the OSU research vessel, the Pacific Storm. The WET-NZ anchors and moorings were then deployed, followed by the WET-NZ itself along with the umbilical cable to connect to the Ocean Sentinel.

Figure 8: TRIAXYS Directional Wave Measurement Buoy

The WET-NZ was tested using the Ocean Sentinel (see Figure 9) for 6 weeks, under varying load and time period specifications, which allowed WEC performance to be characterized while operating in several different control regimes and under a variety of sea conditions. Removal of the system began with the Ocean Sentinel and ended in early October with the WET-NZ.

Figure 9: WET-NZ testing at NETS site with Ocean Sentinel

Note that with the three-point moor used with the Ocean Sentinel to prevent twisting and overextension 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 use a single-point moor that can be deployed all months of the year, e.g., for environmental testing.

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

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

Scaled Testing

While developing the capacity for standardized ocean testing, NNMREC has served developers' testing needs through the O. H. Hinsdale wave tanks. These tanks provide two options for developers as they advance their device designs to test scaled prototype tests. The first, the Large Wave Flume in Figure 10 is equipped with a large-stroke, piston-type wave-maker capable of generating unidirectional waves to simulate tsunamis, hurricane waves and coastal storms. It accommodates roughly 1:10 to 1:30 scale devices. NNMREC has assisted in testing several Columbia Power Technology devices, and the M3 device in this tank, along with a research AWEC discussed previously. The Hinsdale Lab's Tsunami Wave Basin in Figure 11 provides an opportunity to test devices under realistic scaled scenarios, with a multi-segmented piston-type wave-maker capable of generating multidirectional waves. Developers including Columbia Power Technology, M3, WET-NZ and Nepune have tested in this tank. The Tsunami Basin is appropriate for both single devices and arrays; this tank accommodates devices in the 1:33 to 1:100 scale range.

Figure 10: OSU's Large Wave Flume

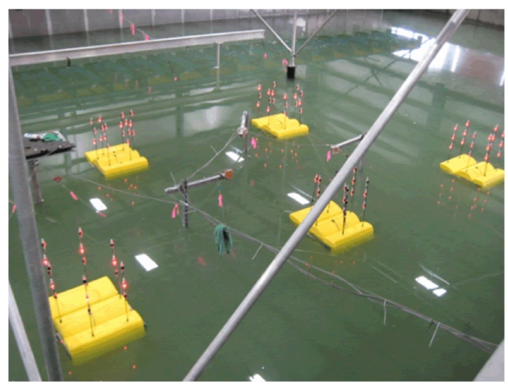


Figure 11: OSU's Tsunami Basin

Discussions with WEC developers about other scaled testing needs have centered on both a smaller tank where one could test 1:100 scale devices at the proof of concept stage, as well as a larger deep water tank where developers could test more realistic mooring systems. There seems to be significant interest in a smaller tank that developers could use to prove prototype concepts more economically, to prepare for Hinsdale testing. Developer interest in the deep water tank appears to be lacking, however, as they express the desire to test in open water at the intermediate scale or go directly to Newport NETS. NNMREC will take these interests into consideration and work with OWET to survey potential test facility users.

While not part of initial plans, NNMREC has recognized developer interest in testing in intermediate scaled open water environments available near the UW, and has supported two such tests. After testing in the Hinsdale wave tanks, Columbia Power Technology went to Puget Sound in February 2011 to test a 1:7 scale device under intermediate scale wave conditions. NNMREC assisted in preparing for the test, and NNMREC faculty at UW engaged in acoustic monitoring for the WEC. Based on this experience, NNMREC has expanded wave energy test support to developers wishing to test in Puget Sound, and to developers testing in Lake Washington. Oscilla Wave Power recently completed a test of their device in Lake Washington with the assistance of Thomson and his team. This work laid the foundation for Oscilla to test at University New Hampshire under DOE funding with the intent of moving back to Newport NETS' full-scale wave energy environment.

PUBLICATIONS

1. A. von Jouanne, T. Lettenmaier, E. Amon, S. Moran, M. Bunn, and A. Yokochi, 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*, 2013.
2. T. Lettenmaier, A. von Jouanne, E. Amon, S. Moran, and A. Gardiner, Testing the WET-NZ Wave Energy Converter using the Ocean Sentinel Instrumentation Buoy, *Marine Technology Society (MTS) Journal*, 2013.
3. A. von Jouanne, T. Lettenmaier, E. Amon, and S. Moran, Wave energy testing using the Ocean Sentinel Instrumentation Buoy, *Proceedings of the 1st Marine Energy Technology Symposium, GMREC-METS13*, WA DC, April 2013.
4. A. von Jouanne, T. Lettenmaier, E. Amon, T. Brekken, and R. Philips, A novel ocean sentinel instrumentation buoy for wave energy testing, *Marine Technology Society Journal*, vol. 47, January-February 2013.
5. A. von Jouanne, T.K.A. Brekken, T. Lettenmaier, E. Amon, and R. Phillips, A novel ocean sentinel instrumentation buoy for wave energy testing, in *Power and Energy Society General Meeting*, San Diego, CA, pp. 1–6, July 2012.
6. A. von Jouanne, T.K.A. Brekken, T. Lettenmaier, E. Amon, and R. Phillips, A novel ocean sentinel instrumentation buoy for wave energy testing, in *OCEANS*, pp. 1–6, 2012.
7. A. Porter, Laboratory observations and numerical modeling of the effects of an array of wave energy converters, MS Thesis, School of Civil & Construction Engineering, Oregon State University, 2012.
8. M. C. Haller, A. Porter, P. Lenee-Bluhm, K. Rhinefrank, E. Hammagren, T. Özkan-Haller, and D. Newborn, Laboratory observations of waves in the vicinity of WEC-arrays, *Proceedings of European Wave and Tidal Energy Conference (EWTEC 2011)*, Paper No.419, 2011.
9. A. von Jouanne and T.K.A. Brekken, Wave energy research, development, and demonstration at Oregon State University, in *Power and Energy Society General Meeting*, Invited paper, Detroit, MI, pp. 1–7, July 2011.
10. E. Amon, T.K.A. Brekken, and A. von Jouanne, A power analysis and data acquisition system for ocean wave energy device testing, *Renewable Energy: An International Journal*, vol. 36, pp. 1922–1930, July 2011.
11. E. Amon, T.K.A. Brekken, and A. von Jouanne, A power analysis and data acquisition system for ocean wave energy device testing, *The Renewable Energy Journal*, 2010.
12. J. Snyder, W. Christensen, R. Chwaszczewski, A. von Jouanne, T. Brekken, and E. Amon, Wave energy mobile ocean test berth, *Energy Ocean*, June 2010.
13. K. Rhinefrank, A. Schacher, J. Prudell, E. Hammagren, C. Stillinger, D. Naviaux, T. Brekken, and A. von Jouanne, Scaled wave energy device performance evaluation through high resolution wave tank testing, in *OCEANS 2010*, Seattle, WA, pp. 1 –6, September 2010.
14. K. Rhinefrank, A. Schacher, J. Prudell, T. Brekken, A. von Jouanne, S. Yim, D. Cox, and et al., High resolution wave tank testing of scaled wave energy devices, in *OMAE*, Shanghai, China, pp. 505–509, June 2010.
15. J. Snyder, W. Christensen, R. Chwaszczweski, A. von Jouanne, T. Brekken, and E. Amon, Wave energy mobile ocean test berth, in *Energy Ocean*, Ft. Lauderdale, FL, June 2010.

ACCOMPLISHMENTS

NNMREC's strategy for tidal energy test facility development has been to develop modular tools and simulation capabilities that allow developers to characterize sites prior to turbine deployment. Over the past five years, these capabilities have been tested in northern Admiralty Inlet, Puget Sound, Washington. The majority of the tidal exchange in Puget Sound moves through Admiralty Inlet and the relative width (5 km) and depth (80 m) of the channel gives rise to currents exceeding 3 m/s. The channel bathymetry is complex and a pair of headlands on the northern and southern sides of the channel (Admiralty Head and Point Wilson, respectively) generate large-scale (e.g., greater than 100 m diameter) eddies on ebb and flood tides. Consequently, the site provides a robust case for instrumentation testing and method development. The collection of velocity data from Admiralty Inlet has informed the development of standards for resource assessment, as well as provided guidance to Public Utility District No. 1 of Snohomish County in its decision to site a tidal energy demonstration project.

Sea Spider Instrumentation Package Deployments

DOE funding supported the initial deployment of the Sea Spider instrumentation package (Figure 12) in April 2009. This is a modular package supporting autonomous instrumentation on a ballasted fiberglass frame. Led by Thomson's group at the Applied Physics Laboratory, the Mark I Sea Spider and its successors (the Mark II and Sonar Spiders) have logged over 40,000 hours of bottom time in Admiralty Inlet without the loss of any instrumentation. Since 2012, Sea Spider deployments have been supported by core grant funding and, when the final tripod is recovered in October 2013, will have completed more than four years of continuous observations. These provide an unparalleled data stream for studying tidal current resources (spatial gradients, predictability), as well as understanding underwater noise in tidal environments. These data are all publicly available through the UW-NNMREC website.

Figure 12: Initial Sea Spider deployment (April 2009)

Tidal Current Resource Characteristics

While the tides (i.e., the change in elevation of the ocean surface) are a well-understood, deterministic process, tidal currents include both deterministic and stochastic processes referred to as turbulence. Between 2005 and 2011, a number of tidal turbine prototypes experienced structural failures, in several cases, due to an incomplete understanding of the tidal currents that they would experience in operation.

Since that time, failures have become rarer, both because of increased factors of safety and an improved understanding of tidal currents. NNMREC has been at the forefront of research in the latter.

Using data from the Sea Spider deployments, Polagye and Thomson in 2013 developed a set of metrics for characterizing variations in the mean current resources. These are now implemented in an open-source Matlab toolbox (depts.washington.edu/nnmrec/characterization) that is in use in the US, UK, Ireland, Canada, and Chile for evaluating site characteristics. In addition, Palodichuk and others demonstrated a method for mapping spatial variations in kinetic power density over distances as short as 100 m using a surface vessel to obtain results to an array of bottom-mounted current profilers. This technique allows project developers to "micro-site" their turbines at low cost and realize power output increases on the order of 10-20%.

Similarly, Thyng in 2012 utilized a high-resolution numerical model (ROMS) to simulate tidal currents in northern Admiralty Inlet. These simulations show good qualitative agreement with measurements and reveal a complex pattern to currents throughout northern Admiralty Inlet. However, quantitative agreement in power density was only fair, with the simulations under-predicting resource intensity by a factor of two. This suggests that numerical models can play an important role in support of project siting, but that verification against measurements is an essential step.

Through Polagye's work on the IEC TC-114 standards committee, this research has strengthened international standards for tidal resource assessment and power performance characterization.

Turbulence

Thomson and team in 2012 provided the first rigorous investigation of turbulence characteristics at two tidal energy sites in Puget Sound. This research, undertaken in conjunction with Pacific Northwest National Laboratory and the NREL, underpins NREL's turbulence simulator (Hydro TurbSim) and has been used by several international groups to investigate extreme loads on turbine blades. Recently, Thomson's group reported a set of turbulence measurements from 10-15 m above the seabed using compliantly-moored Doppler velocimeters with motion correction packages. These measurements are helping device developers around the world better understand their design loads and adopt appropriate, rather than uneconomically conservative, factors of safety for device design.

PUBLICATIONS

1. T. Kutney, R. Karsten, and B. Polagye, Priorities for reducing tidal energy resource uncertainty, *European Wave and Tidal Energy Conference*, Aalborg, Denmark, September, 2013.
2. B. Polagye and J. Thomson (under revision) A leading-order noise correction for acoustic Doppler current profiler measurements at hydrokinetic energy sites (technical communication), *IEEE J. Ocean. Eng.*
3. V. Durgesh, M. Richmond, J. Thomson, and B. Polagye (under revision) Noise correction of turbulent spectra obtained from Acoustic Velocimeters, *Flow Measurement and Instrumentation.*
4. J. Thomson, L. Kilcher, M. Richmond, J. Talbert, A. deKlerk, B. Polagye, M. Guerra, and R. Cienfuegos, Tidal turbulence spectra from a compliant mooring, *Proceedings of the 1st Marine Energy Technology Symposium, GMREC-METS13*, Washington, DC, 2013.

5. B. Polagye, and J. Thomson, Implications of tidal phasing for power generation at a tidal energy site, *Proceedings of the 1st Marine Energy Technology Symposium, GMREC-METS13*,, Washington, DC, 2013.
6. B. Polagye, and J. Thomson, Tidal energy resource characterization: methodology and field study in Admiralty Inlet, Puget Sound, US, US, *Proc. Inst. MechE, Part A: J. Power and Energy*, doi: 10.1177/0957650912470081.
7. M. Palodichuk, B. Polagye, and J. Thomson, Resource mapping at tidal energy sites, *IEEE J. Ocean. Eng.,* doi: 10.1109/JOE.2012.2227578.
8. J. B. Richard, J. Thomson, B. Polagye, and J. Bard, Method for identification of doppler noise levels in turbulent flow measurements dedicated to tidal energy, *European Wave and Tidal Energy Conference*, 2013.
9. K. Thyng, J. Riley, and J. Thomson, Turbulence in a tidal channel: models and data, *Physics of Estuarine and Coastal Seas*, 2013.
10. J. Thomson, M. Richmond, B. Polagye, and V. Durgesh, Measurements of turbulence at two tidal energy sites, *J. Ocean. Eng.,* 37, 2012.
11. B. Polagye, J. Thomson, and M. Palodichuk, Multiscale tidal resource characterization: a case study of Admiralty Inlet, Puget Sound, WA, USA, *International Conference on Ocean Energy*, 2012.
12. M. Kawase, and K.M. Thyng, Three-dimensional hydrodynamic modeling of inland marine waters of Washington State, United States, for tidal resource and environmental impact assessment, *IET Renewable Power Generation*, 4, 568–578, 2010.
13. J. Epler, B. Polagye, and J. Thomson, Shipboard acoustic doppler current profiler surveys to assess tidal current resources, *Oceans 2010*, Seattle, WA, 2010.
14. J. Thomson, M. Richmond, B. Polagye, and V. Durgesh, Quantifying turbulence for tidal power applications, *Oceans 2010 MTS/IEEE*, Seattle, WA, 2010.
15. B. Polagye, J. Epler, and J. Thomson, Limits to the predictability of tidal current power, *Oceans 2010 MTS/IEEE*, Seattle, WA, 2010.
16. S. Gooch, J. Thomson, B. Polagye, and D. Meggitt, Site characterization for tidal power, *Oceans 2009 MTS/IEEE*, Biloxi, MS, 2009.

INVESTIGATE COMPATIBILITY OF MARINE ENERGY TECHNOLOGIES WITH ENVIRONMENT, FISHERIES AND OTHER MARINE RESOURCES

ACCOMPLISHMENTS

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

1. Characterization of habitat and benthic species around the around the Newport NETS where the Ocean Sentinel was to be deployed off Newport, Oregon;
2. Description of gray whale migratory pathways off Newport, Oregon;
3. Characterization of the ambient noise field and recording of the Ocean Sentinel/WEC acoustic outputs;
4. Initial deployments of an in-house developed EMF measurement instrumentation and baseline characterization at the NETS.

During phase 1 funding, Dr. Sarah Henkel and her team conducted initial environmental site characterization work at and around the NETS. Physical site characterization described water quality and sediment characteristics (grain size and total organic carbon and nitrogen) across depth at the site and across seasons and years. Biological characterization consisted of identifying and enumerating organisms living within the sediment, on the surface of the sediment, and bottom-associated fishes. Because this work was initiated early in the project, baseline pattern of spatial, seasonal, and inter-annual variability have been characterized. This is important for evaluating potential future project effects and has helped the industry in two ways. The first has been in potentially lowering the bar of what will be required for baseline studies for future projects. The intensive sampling conducted for the NETS and the subsequent analyses can inform us as to the spatial and temporal intensity of benthic sampling to adequately characterize future proposed installation sites. Second, establishing the range of what is “natural” allows any changes to benthic habitats or species that may be observed after installation to be put into context.

Also during Phase 1, groups at the HMSC initiated marine mammal research that can be used for baseline against which to compare future behavioral research around wave energy facilities. Marine Mammal Institute teams at HMSC conducted surveys of gray whales migrating in the vicinity of the NETS. They described the depth and distance to shore that gray whales travel during the three phases of their migration. This work will allow researchers to determine if future WEC array installations result in deviations from the whales’ migratory paths.

In Phase 2, Haxel conducted initial acoustic characterization of the NETS area using passive hydrophones deployed on a bottom lander. This year-long survey characterized the acoustic environment, identifying ship traffic, wind, rain, and waves crashing on the beach. It was important to quantify the noise levels of the ocean prior to any deployments in order to manage expectations about what the noise field would be like after deployment and if devices would be able to be detected above ambient conditions. Additionally, the passive acoustic hydrophones recorded low-frequency marine mammal vocalizations, allowing for identification of more species utilizing that space than visual surveys alone. Through the baseline work, Haxel determined that 10% of the recordings were above the 120dB threshold for marine mammal harassment in the natural ocean. Initial acoustic assessment of existing wave energy facilities were conducted by Haxel during WEC testing in summer 2012 using towed passive hydrophones.

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

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

Some tasks for Phase 2 were altered to produce better work products and reduce redundancy. For example, during the course of this project, a number of national and international entities launched websites and/or literature reviews focused on environmental information. Rather than produce another website and fracture readership, NNMREC partnered closely with PNNL to make their Tethys system as comprehensive as possible. Additionally, Dr. Henkel participated in the Annex IV efforts.

Currently, the researchers at HMSC are continuing the work they have been doing at the NETS (including pre- and post-installation surveys associated with each WEC deployment) and adding benthic and acoustic surveys at the future PMEC site. Additionally, Suryan's team is undertaking baseline bird surveys to characterize habitat utilization of various species of concern. The Marine Mammal group has been experimenting to determine the potential effectiveness of an acoustic deterrent device that emits a sound similar to a killer whale and is intended to cause gray whales to slightly shift their swimming trajectory. If devices are not actually noisy enough for marine mammals to detect above ambient ocean noises, the deterrent device may be used in order to prevent whale encounters with WEC device components. As part of the Phase 3 deliverables, NNMREC is in the early stages of planning a workshop on detecting EMF and assessing EMF effects on marine species of concern.

Advising industry, agencies and other stakeholders on environmental effects is a continually on-going activity. Henkel and Boehlert lead the wave energy portion of the NOPP Protocols Framework project. Boehlert and Henkel also convened the BOEM-sponsored Environmental Effects Workshop in November

2012 (http://hmsc.oregonstate.edu/rec/). Recently, Henkel collaborated with M3 Wave Energy to develop environmental study plans for a demonstration deployment of their devices. Henkel regularly gives presentations and does outreach to the public on potential environmental effects and the studies underway to address them.

Research on the environmental effects of tidal energy development have centered around the outcome of a 2010 technical workshop hosted by NNMREC on the University of Washington campus. This meeting brought together over 70 experts from around the world to evaluate the potential significance and current level of uncertainty around tidal energy development at both pilot and commercial scales of development.

As with WECs, the sound produced by tidal converters could be environmentally significant if it alters marine animal (invertebrate, fish, or marine mammal) behavior in a biologically meaningful manner. This class of problem draws a number of parallels to US Navy research investments in the area of Population Consequences of Acoustic Disturbances (PCAD). Owing to the difficulty of deploying hydrophones in high current environments, the soundscape at sites suitable for tidal energy development had not been previously characterized. Bassett presents the first comprehensive picture of ambient noise in these environments, investigating the contributions from vessel traffic, sediment generated noise, and turbulence, respectively. This information was used to conduct the first probabilistic assessment of the detection of turbine sound by marine animals, as described in a peer-reviewed publication co-authored by NNMREC, NOAA National Marine Fisheries Service, and OpenHydro.

In addition, Thomson and Polagye have demonstrated several types of new instrumentation for observing marine life around wave and tidal energy converters. This work included a test of land-based infrared imaging to detect and classify Southern Resident killer whales under a broader set of environmental conditions (night, light fog, light rain) than is possible with visual spectrum cameras. In addition, NNMREC has hosted a dissolved oxygen sensor provided by the Washington Department of Ecology on the Admiralty Inlet Sea Spider platform. This partnership demonstrates the long-term potential for marine renewable energy platforms to serve as ocean observatories.

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

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

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

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

PUBLICATIONS

1. B. Polagye, C. Bassett, M. Holt, J. Wood, and S. Barr, A framework for detection of tidal turbine sound: A pre-installation case study for Admiralty Inlet, Puget Sound, Washington (USA), Submitted to *IEEE J. Ocean. Eng.*
2. M. Kawase and M. Gedney, Tidal energy extraction in an idealized ocean-fjord tidal model with astronomical forcing, to be presented at *10th European Wave and Tidal Energy Conference (EWTEC)*, Aalborg, Denmark, September 2-5, 2013.
3. S. K. Henkel, F. Conway, and G. Boehlert, Environmental and human dimensions of ocean renewable energy development. *IEEE* 101(4), 2013.
4. S. K. Henkel, R. M. Suryan, and B. Lagerquist, *Marine renewable energy and environmental interactions: baseline assessments of seabirds, marine mammals, and benthic communities on the Oregon shelf In humanity and the sea: Marine Renewable Energy*. Ed. MA Shields and A Payne. Springer (In press).
5. M. C. Haller, and T. Özkan-Haller, Physical-environmental effects of wave and offshore wind energy extraction: a synthesis of recent oceanographic research, in: G. Boehlert, C. Braby, A. S. Bull, M. E. Helix, S. Henkel, P. Klarin, and D. Schroeder, eds., *Oregon Marine Renewable Energy Environmental Science Conference Proceedings*, U.S. Department of the Interior, Bureau of Ocean Energy Management, Cooperative Agreement with Oregon State University M12AC00012, OCS Report BOEM 2013-0113, http://hdl.handle.net/1957/36650, 2013.

6. C. Bassett, J. Thomson and B. Polagye, Sediment-generated noise and bed stress in a tidal channel, *J. Geophys. Res.*, 118, 2013.
7. A. Schultz, Section 5: Exposure Characterization, in: *EPRI Workshop on EMF and Aquatic Life*. EPRI, Palo Alto, CA, 2013
8. A. K. Porter, M.C. Haller, and P. Lenee-Bluhm, Laboratory observations and numerical modeling of the effects of an array of wave energy converters, *in Proceedings of 33rd ICCE*, Santander, Spain, 2012.
9. C. Bassett, B. Polagye, M. Holt, and J. Thomson, A vessel noise budget for Admiralty Inlet, Puget Sound, WA, *Journal of the Acoustics Society of America*, 132, 2012.
10. B. Polagye, B. Van Cleve, A. Copping, and K. Kirkendall, eds., 2011, Environmental effects of tidal energy development. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS F/SPO-116, 186 pp.
11. M. Slater, A. Schultz, R. Jones, and C. Fischer, Electromagnetic field study: Technical Report on behalf of Oregon Wave Energy Trust, 2011.
12. J. Graber, J. Thomson, B. Polagye, and A. Jessup, Land-based infrared imagery for marine mammal detection*, SPIE Remote Sensing and Modeling of Ecosystems for Sustainability VIII*, 2011.
13. M. C. Haller, A. Porter, P. Lenee-Bluhm, K. Rhinefrank, D. Newborn, and T. Özkan-Haller, Experiments on the near-field and far-field wave effects of WEC arrays*, Abstract Proceedings EGU General Assembly*, Vienna, 2011.
14. C. Bassett, J. Thomson, and B. Polagye, Underwater noise measurements from a 1/7 scale wave energy converter, *Oceans 2011*, Hawaii, 2011.
15. C. Bassett, J. Thomson, and B. Polagye, Characterizing underwater noise at a tidal energy site, *Ocean 2010 MTS/IEEE*, Seattle WA, 2010.

ACCOMPLISHMENTS

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

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

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

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

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

To gather data about breaking waves and effects on buoys, Paasch's team is developing small data buoys that are specifically design to detect breaking waves in the open ocean.

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

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

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

Another aspect of reliability and survivability research at NNMREC involves material properties and biofouling. During the preparation of the original NNMREC proposal, discussions between Yokochi and WEC developers indicated that a significant unknown in device operation was the longevity of biofouling protection coatings in very long deployments and how the coatings might impact the maintenance cycle for devices. A clearly expressed desire was to enable coatings to exhibit acceptable performance over lifetimes of 20 or more years without requiring frequent haul out and hull treatments. Therefore, Yokochi proposed to investigate the performance of biofouling prevention technologies based on electrochemically generated hypochlorite ions by seawater oxidation.

Through this project, Yokochi's team determined the minimum potential required to enable electrochemical biofouling prevention of critical surfaces (ca. 1.05V vs. NHE), and developed and is currently validating coupled reaction/transport model for the electrochemical biofouling prevention process. It appears that the electrochemical biofouling prevention technologies have the potential to be extremely useful in the development of marine energy devices, given that no depletion of active chemicals will occur in the likely lifetime of the marine energy system. By utilizing a carbon black / graphite / polymer matrix composite that can be deployed as a conformal coating, the technology has the potential to protect odd locations in a device. Further, by not releasing known chemicals with significant environmental impacts (e.g., release of Cu(II) or biocides into the environment) the electrochemical biofouling prevention technology is likely to have lower environmental impacts than biocidal coatings. This lower release of synthetic chemicals into the environment would enhance the "green" credentials of marine energy, but is only an assumption until an accurate life cycle assessment is carried out evaluating the alternatives.

PUBLICATIONS

1. S. Casey, B. Batten, and R. Paasch, Comparison of passive and active controlled hydraulic power take off systems for wave energy conversion, in *Proceedings of the 1st Marine Energy Technology Symposium, GMREC-METS13*,, April 10-11, Washington, D.C., 2013.
2. S. Meicke, and R. Paasch, Seawater lubricated polymer journal bearings for use in wave energy converters, *Renewable Energy* 39: 463-470, 2012.
3. M.T. Koopmans, S. Meicke, I. Y. Tumer, R. Paasch, Experimental Polymer Bearing Health Estimation and Test Stand Benchmarking for Wave Energy Converters, *Annual Conference of the Prognostics and Health Management Society*, Montreal, QB, September 2011.
4. P. Lenee-Bluhm, R. Paasch and T. Ozkan-Haller, Characterizing the wave energy resource of the US Pacific Northwest, *Renewable Energy* 36: 2106 – 2119, 2011.
5. C. Stillinger, T.K.A. Brekken, A. von Jouanne, R. Paasch, D. Naviaux, K. Rhinefrank, J. Prudell, A. Schacher, and E. Hammagren, WEC prototype advancement with consideration of a real-time damage accumulation algorithm, in *PowerTech*, Trondheim, Norway, pp. 1–8, June 2011.
6. Brown, R. Paasch, I. Tumer, P. Lenne-Bluhm, J. Hovland, T. Brekken, and A. von Jouanne, Towards a definition and metric for the survivability of ocean wave energy converters, in *ASME International Conference on Energy Sustainability*, Phoenix, AZ, pp. 917–927, May 2010.
7. J. Hovland, R. Paasch, and M. Haller, Characterizing dangerous waves for ocean wave energy converter survivability, *Proc. of 29th Intl. Conf. on Ocean, Offshore and Arctic Eng.*, ASME, Shanghai, Paper No. OMAE2010-20421, 2010.
8. W. Zhang and S. Yim, A multiphysics multiscale 3-D computational wave basin model for wave impact load on a cylindrical structure, *Journal of Disaster Research*, vol. 4, pp. 450-461, 2009.

ACCOMPLISHMENTS

A screening test was conducted to identify composite material system(s) that exhibit good long-term durability when continuously exposed to salt-water. This topic is of interest because tidal turbines will likely be produced using composites. Four composite material systems were considered: fiberglass/epoxy, fiberglass/vinylester, a carbon/epoxy material produced using "wet" layup techniques, and a carbon/epoxy material produced using aerospace-grade pre-preg. Panels of these four material systems were submerged and exposed to in situ conditions at a potential tidal energy site. It was hypothesized that degradation caused by salt-water exposure would likely be associated with degradation of the polymeric matrix rather than degradation of the reinforcing fiber. Consequently the shear modulus of the panels was monitored, since this property is particularly sensitive to the polymeric matrix. A reduction in shear modulus following exposure was observed for all four material systems considered. The reductions for the fiberglass/epoxy, fiberglass/vinylester, carbon/epoxy material produced using "wet" layup, and carbon/epoxy material produced pre-preg were 66%, 13%, 26%, and 7%, respectively. In addition, three panels of the fiberglass/vinylester system were exposed to an accelerated testing regime in the laboratory, and the change in shear modulus due to this exposure was observed. The shear modulus of these panels were reduced by 38%, 33% and 33% following 30 days of exposure to artificial saltwater at 30˚C, 40˚ C, and 50˚C, respectively. While these results demonstrated that elevated temperature causes shear modulus degradation and can therefore be used as an accelerating agent, additional laboratory tests are required to predict long-term in-situ behavior.

It is recommended that tidal energy device developers interested in using composites should focus future developmental efforts either on fiberglass/vinyl ester composites, due to their low cost and reasonable long-term durability, or on relatively higher-costs carbon fiber/epoxy pre-preg systems, due to their superior long-term durability. In addition to these composite durability tests, the Sea Spider tripods have been used to screen for biofouling and corrosion. Hempel, S.A. (Denmark) provided a series of coupons coated with variants of their NuSil product for static endurance testing in Admiralty Inlet. The initial set of coupons experienced delamination due to incorrect preparation; a second set of coupons has performed well, with no fouling or delamination. Similarly, NNMREC is currently testing several sets of metallic fasteners for OpenHydro to identify any combinations that are particularly susceptible to corrosion in Admiralty Inlet.

PUBLICATIONS

1. A. Ogg, Screening Tests of Composites for use in Tidal Energy Devices, Masters Thesis, University of Washington. 2011.

COLLABORATION/OPTIMIZATION WITH MARINE RENEWABLE AND OTHER RENEWABLE ENERGY RESOURCES

ACCOMPLISHMENTS

This task focused on engaging NREL in support of connecting MHK technologies to each other and to other renewable energy sources. To this end, NREL provided technical input for mooring and cabling design during the design process for the initial mobile ocean test berth that evolved into the Ocean Sentinel. NREL supported the first test at NETS through constructing a test plan for the open-water testing of the WET-NZ device with the Ocean Sentinel. NREL also contributed a suite of sensors and a data acquisition system for the test. NREL assisted Northwest Energy Innovation and NNMREC in preparing their various systems for deployment and participated in the mobilization and deployment of the device.

As evidenced at a meeting in Ireland in 2012 of global testing facility leaders, testing guidelines and plans are currently without standards. And yet, testing of technology in a systematic, traceable, consistent and manner is essential to advancing wave energy technologies. MHK technologies are being field-testing throughout the world and many test guidelines have been developed and international standards are now being developed. However, no comprehensive and generally accepted testing documentation exist. NREL worked with NNMREC to develop a guideline that brings together testing procedures and standards from the MHK industry, along with guidelines and standards from other sectors, such as the wind industry, the U.S. Coast Guard, and offshore oil and gas. NREL is working with NNMREC to create a device-generic test plan and data analysis document to act as a starting point for designing deployment specific test plans in the future.

In preparation for summer 2013 research and testing at NETS, NREL's offshore instrumentation team is assisting NNMREC to outfit the Ocean Sentinel with the ability to collect mooring line load data. NREL will work with NNMREC on system design and specifications and software integration along with data analysis after the testing is completed.

NREL's Grid Integration Group is supporting NNMREC's efforts to design and build a grid emulator. NREL is leveraging recent experience in designing both a land-based and an offshore wind grid simulator with similar design objectives. NREL will continue to support the project with guidance and design reviews.

The tasks described reflect a deviation in the initially envisioned plans for NREL team integration. Working with NNMREC management, it was determined that greater value could be delivered to NNMREC's objectives if NREL's efforts focused on directly supporting the establishment of the wave test center rather than exploring the synergies between wave energy and other renewable resources. NREL has continued to work with NNMREC management to adapt efforts to align with evolving priority needs.

PUBLICATIONS

1. D. Halamay and T.K.A. Brekken, Factorial analysis for modeling large-scale grid integration of renewable energy sources, in *PowerTech*, Trondheim, Norway, pp. 1–6, June 2011.
2. D. A. Halamay, T.K.A. Brekken, A. Simmons, and S. McArthur, 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, 2011.
3. D. Halamay and T.K.A. Brekken, Monte Carlo analysis of the impacts of high renewable power penetration, in *Energy Conversion Congress and Exposition (ECCE)*, Phoenix, AZ, pp. 3059–3066, September 2011.
4. D. Halamay, S. McArthur, and T.K.A. Brekken, A methodology for quantifying variability of renewable energy sources by reserve requirement calculation, in *Energy Conversion Congress and Exposition (ECCE)*, Atlanta, GA, pp. 666–673, September 2010.
5. S. McArthur and T.K.A. Brekken, Ocean wave power data generation for grid integration studies, in *IEEE Power and Energy Society General Meeting,* Minneapolis, MN, pp. 1–6, July 2010.
6. D. Halamay, T.K.A. Brekken, A. Simmons, and S. McArthur, Reserve requirement impacts of large-scale integration of wind, solar, and ocean wave power generation, in *IEEE Power and Energy Society General Meeting*, Minneapolis, MN, pp. 1–7, July 2010.

ACCOMPLISHMENTS

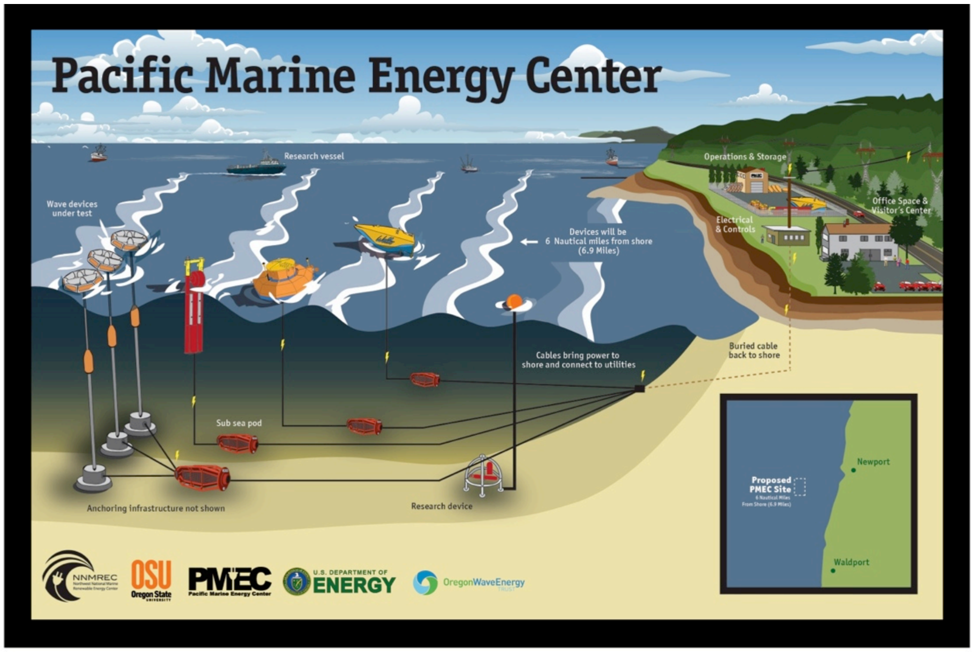
In building out the Newport NETS, it became clear that a grid connected utility scale testing facility for WECs was needed in the US, one that provided a fully energetic wave environment that developers would encounter in deploying on the US west coast. At the time of original NNMREC proposal submission, investigators assumed that a mobile berth like Ocean Sentinel could be developed at the 1MW scale; through the design process, they discovered that such a scale was challenging from an engineering perspective and prohibitively expensive (upwards of $8 - $10 million).

Therefore, in Fall 2011, NNMREC contracted a feasibility study for a grid-connected utility scale WEC test facility off of the Oregon coast. While one option would have been to grid-connect the NETS site, WEC developers were requesting deeper water in which to test, and the utilities suggested there might be better places to connect to the grid. Through the feasibility study, four communities were identified as possible homes for this utility scale test facility that came to be known as the Pacific Marine Energy Center (PMEC).

In October 2012, DOE provided initial funding to begin work on the PMEC facility. The effort includes high-level tasks of site selection, market and supply chain analysis, permitting strategy and execution, site characterization and environmental study, utility interconnection strategy, engineering pre-design, and instrumentation design. In January 2013, NNMREC completed an extensive public outreach and engagement process to locate PMEC, and selected Newport Oregon; this process is described in the section of this report on Outreach and Engagement. Since January, NNMREC has formed a regulatory subcommittee that meets on a regular basis. Through these meetings, a collaborative process is informing the PMEC permitting strategy.

PMEC is planned to have four berths at which individual or small arrays (3 – 5) of devices might test. It is expected to be permitted for up to 10 WEC devices at any given time and up to 10 MW of electricity provided to the grid. The site is expected to have one cable for each berth, buried to shore, and then connected to an onshore facility where electrical control instrumentation would be located. From that point the power would connect to the grid.

In addition to PMEC site development, Polagye is leading the development of an Adaptable Monitoring Package (AMP) that will enable power and data hungry observations of wave and tidal energy converters. For example, the optical-acoustical camera system (Joslin et al. 2012) generates 100 MB/s of raw data when capture images at 10 frames per second and draws almost 200 W of power. The AMP is a streamlined instrumentation package that can be connected to a wet-mate plug on either a wave or tidal converter using an off-the-shelf inspection-class ROV (SeaEye Falcon) and customized tool skid. The AMP will be a piece of critical infrastructure for PMEC and also be used by Snohomish Public Utility District for its tidal energy demonstration project in Admiralty Inlet.



PUBLICATIONS

1. J. Joslin, G. Cook, C. Roper, A. Stewart, and B. Polagye, Development of an Adaptable Monitoring Package for marine renewable energy, *MTS/IEEE Oceans 2013*, San Diego, September 2013.
2. J. Joslin, B. Polagye, and S. Parker-Stetter, Development of a stereo camera system for monitoring hydrokinetic turbines, *MTS/IEEE Oceans 2012*, Hampton Roads, VA, October 19-14, 2012.
3. J. Klure, Feasibility study for a grid connected Pacific Marine Energy Center, NNMREC Technical Report, December 2012.

OVERVIEW PUBLICATIONS

1. K. Ruehl, J. Hovland, S. Meicke and R. Paasch, Wave Energy, a Pacific Perspective, *Philosophical Transactions of the Royal Society A*, 370: 481-501, 2012.
2. T.K.A. Brekken, B. Batten, and E. Amon, "From blue to green [ask the experts]," *IEEE Control Systems Magazine*, vol. 31, pp. 18–24, Oct. 2011.
3. T.K.A. Brekken, A. von Jouanne, and A. Yokochi, Ocean wave energy overview and research at Oregon State, in *poster at Ocean Sciences Meeting*, Portland, OR, February 2010.
4. T.K.A. Brekken, A. von Jouanne, and H. Han, Ocean wave energy overview and research at Oregon State University, in *Proceedings of Power Electronics and Machines in Wind Applications (PEMWA)*, Lincoln, NE, pp. 1–7, June 2009. Invited paper.

TECHNICAL PRESENTATIONS

1. B. Polagye, “Marine Renewable Energy and the Environment: Experience to Date”, Efectos Ambientales de la Extracción de Energía Marina, Pontificia Universidad de Catholica, May 7, 2013.
2. B. Polagye, “Tidal Energy Resources, Technology, and Research”, University of Washington Water Symposium, April 30, 2013.
3. B. Batten, “Ocean Energy: the Wave of the Future”, Warren and Leta Giedt Invited Lecture, UC Davis, April 18, 2013.
4. B. Polagye, “Cross-flow Turbine Performance and Wake Characterization”, 1st Annual Marine Energy Technology Symposium 2013, Washington DC, April 2013.
5. B. Polagye, “Implications of Tidal Phasing for Power Generation at a Tidal Energy Site”, 1st Annual Marine Energy Technology Symposium 2013, Washington DC, April 2013.
6. D. Sale, “Structural Optimization of Composite Blades for Wind and Hydrokinetic Turbines”, 1st Annual Marine Energy Technology Symposium 2013, Washington DC, April 2013.
7. S. Casey, “1st Annual Marine Energy Technical Symposium 2013, Washington DC, April 2013.
8. B. Batten, “Monitoring at the North Ocean Energy Test Site, Newport Oregon”, DOE MHK Environmental Monitoring Workshop, April 2013.
9. B. Polagye, “Development of an Adaptable Monitoring Package for Marine Renewable Energy Projects”, DOE MHK Environmental Monitoring Workshop, April 2013.
10. S. Moran, “Wave Energy Testing Using the Ocean Sentinel Instrumentation Buoy”, 1st annual Marine Energy Technical Symposium 2013, Washington DC, April 2013.
11. B. Batten “Ocean Testing with the Northwest National Marine Renewable Energy Center”, panelist, Future Energy Conference, Portland, OR April 2013.
12. B. Batten “Ocean Testing with the NNMREC”, panelist, Global Marine Renewable Energy Conference, Washington, DC April 2013.
13. B. Polagye “Research with NNMREC”, panelist, Global Marine Renewable Energy Conference, Washington, DC April 2013.
14. A. Schultz, Invited speaker at Electric Power Research Institute conference on Aquatic Life and Electromagnetic Fields, Monterey, CA, 2013.
15. G. Garcia, “An Inner-Shelf Wave Forecasting System for the US Pacific Northwest”, WISE meeting 2013, April 2013.
16. M. Haller, “Some results on the modeling of the far-field effects of WEC-Arrays”, International Coastal Symposium 2013, Plymouth, U.K., April 9, 2013.
17. A. Yokochi, “Recent Developments at the NNMREC”, Wave Energy Centre (WavEC), Lisbon, Portugal, February 2013.
18. A. Alberto, “Calibration of Discrete Random Walk (DRW) Model via G.I Taylor's Dispersion Theory.” APS 65th DFD Meeting. San Diego, CA. USA. November 18-20, 2012.
19. B. Polagye, “Multi-scale tidal resource characterisation: A case study for Admiralty Inlet, Puget Sound”, ICOE, Dublin Ireland, October 2012.
20. B. Polagye, “Tidal Energy Resource Characterization”, Hydraulics and Maritime Research Centre, Cork Ireland, October 2012
21. B. Batten, “Northwest National Marine Renewable Energy Center”, Annex V, Dublin Ireland, October 2012.
22. B. Batten, “Ocean Energy: the Wave of the Future?”, AAAS Cutting Edge Energy, UC Berkeley, October 2012.
23. B. Batten, Oregon Renewable Energy Conference, Portland, OR September 2012.
24. B. Polagye, “Prioritizing Environmental Monitoring: Lessons from a Tidal Energy Project”, Oregon Renewable Energy Conference, Portland, OR September 2012.

25. B. Batten, “Northwest National Marine Renewable Energy Center: Vision, Progress & Goals”, Bureau of Ocean Energy Management Oregon Task Force Meeting, April 2012.
26. A. Alberto, “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. USA. November 18-20, 2012.
27. A. Alberto, “Numerical modeling of the effects of a free surface on the operating characteristics of Marine Hydrokinetic Turbines.” APS 65th DFD Meeting. San Diego, CA. USA. November 18-20, 2012.
28. M. Bunn, and A. Yokochi, “Long Term Biofouling Protection of Surfaces in Seawater Using Electrochemical Methods” 2012 Annual Meeting of the AIChE, November 2012.
29. A. von Jouanne, *Riding the Waves: Harnessing Ocean Wave Energy through Research, Development and Testing,* UC Irvine, October 18th, 2012.
30. A. von Jouanne, “Advanced Life Extending Control of Multiple Energy Storage Solutions to Reduce Load-Following Dependency and Wear on the Hydro-Power System”, BPA Seminar, Jan. 11th, 2012.
31. T. Lewis, “Modeling and Control of a Slack-Moored Two-Body Wave Energy Converter with Finite Element Analysis”, ECCE, Sept. 2012. Prize Top Student Oral Presenter Award.
32. Garcia, G., “Wave Predictions along the Oregon and Southwest Washington Coasts,” International Conference on Coastal Engineering, July 2012.
33. S. Kassem, “Forecasting the wave-current interactions at the Mouth of the Columbia River, OR, USA,” International Conference on Coastal Engineering, July 2012.
34. G. Garcia, “Nearshore Wave Predictions along the Oregon and Southwest Washington Coasts,” Oregon Sea Grant Scholars Day Symposium.
35. G. Garcia, “Nearshore Wave Predictions along the Oregon and Southwest Washington Coasts”, AGU Fall Meeting, December 2012.
36. B. Polagye, “Northwest National Marine Renewable Energy Center, Federal Renewable Ocean Energy Working Group”, Washington, DC, April 27, 2012.
37. B. Polagye, “A Framework for Assessing Marine Mammal Detection of Sound Produced by Tidal Turbines,” National Marine Fisheries Service Marine Mammal Working Group, July 24, 2012.
38. B. Polagye, “Case study example: Alternative energy – tidal energy”, Pacific Northwest Waters Workshop, Redmond, WA, February 2, 2012.
39. M. Bunn, “Current Results in the Electrochemical Protection of Surfaces in Seawater from Biofouling” 2012 ACS Northwest Regional Meeting (NORM 2012), July 2012.
40. B. Batten, “Ocean Energy: the Wave of the Future?”, Vinson Lecture, University of Delaware, February 2012.
41. A. Yokochi, “Overview of the NNMREC” National Institute for Standards and Technology (NIST), March 2012.
42. M. Kawase, Effects of localized energy extraction in an idealized, energetically complete numerical model of an ocean-estuary tidal system, EIMR International Conference, Kirkwall, Orkney, United Kingdom, May 1, 2012 and US Department of Energy Marine and Hydrokinetic Instrumentation, Measurement and Computer Modeling Workshop, Broomfield, Colorado, July 10, 2012.
43. S. Moran, Ocean Renewable Energy Conference VII, Portland, OR. Presented: “What We Learn from Device Testing.” September 26-27, 2012.
44. S. Henkel, Oregon Marine Renewable Energy Conference, Corvallis, Oregon - Linking Habitat and Benthic Invertebrate Species Distributions in Areas of Potential Renewable Energy Development. November 28, 2012.
45. S. Henkel, Environmental Interactions of Marine Renewables: Orkney, Scotland - Assessing Potential Ecological Effects of Wave Energy Development in the Pacific Northwest: Activities of the Northwest National Marine Renewable Energy Center, (Invited Keynote) May 1, 2012.
46. S. Henkel, P/ICES Early Career Scientists in Ocean Change Meeting: Mallorca, Spain - Addressing Potential Interactions of Ocean Renewable Energy Development and Benthic Communities, April 24, 2012.
47. S. Henkel, Oregon AFS: Eugene, Oregon - Benthic Monitoring for Offshore Renewable Energy, March 1, 2012.

48. S. Henkel, Benthic Ecology Meeting: Norfolk, Virginia - Spatial Heterogeneity of Pacific Northwest Infauna Increases with Grain Size, March 20, 2012.
49. S. Henkel, Western Groundfish Conference. Seattle, Washington - Dynamics of juvenile flatfish and their prey in coastal benthic habitats. (Co-author with student C. Clark) Feb. 8, 2012.
50. J. Thomson, PSC Environmental Science and Technology Practicum, 2012.
51. A. von Jouanne, "A Novel Ocean Sentinel Instrumentation Buoy for Wave Energy Testing", PES 2012, San Diego, CA, July 2012.
52. E. Amon, Marine and Hydrokinetic Instrumentation, Measurement & Computer Modeling Workshop, Broomfield, CO. Presented: "Instrumentation for WEC Testing at NNMREC-OSU Facilities." July 9-11, 2012.
53. A. Schultz, Invited speaker, China University of Geosciences, Wuhan, 2012.
54. M. Haller, "Wave Energy Research at Oregon State University", Civil Engineering Design Seminar, Boğaziçi University, Istanbul, Turkey, March 16, 2012.
55. A. K. Porter, M.C. Haller, and P. Lenee-Bluhm, Laboratory observations and numerical modeling of the effects of an array of wave energy converters, in Proceedings of 33rd ICCE, Santander, Spain, 2012.
56. M. Haller, "Physical Environmental Effects of Wave and Offshore Wind Energy Extraction: A synthesis of recent oceanographic research", Oregon Marine Renewable Energy Environmental Science Conference, Corvallis, OR, November 28-29, 2012.
57. J. Thomson, "Field Measurements of Turbulence at Tidal Energy Sites", NREL Instrumentation, Measurement and Computer Modeling Workshop, Broomfield, CO July 2012.
58. D. Sale, "HARP Opt: An Optimization Code for System Design of Axial Flow Turbines", NREL Instrumentation, Measurement and Computer Modeling Workshop, Broomfield, CO July 2012.
59. M. Kawase, "Effects of Localized Energy Extraction in an Idealized, Energetically Complete Numerical Model of an Ocean-Estuary Tidal System", NREL Instrumentation, Measurement and Computer Modeling Workshop, Broomfield, CO July 2012.
60. T. Brekken, Presentation of "A novel ocean sentinel instrumentation buoy for wave energy testing," at the 2012 Power and Energy Society General Meeting.
61. A. von Jouanne, *OSU Wind, Wave and Energy Storage Research & Developments*, National Rural Electric Cooperatives Association's (NRECA) Cooperative Research Network (CRN), Nov. 9th, 2011.
62. A.F.T. Yokochi, "Studies on Current Approaches for Biofouling Protection of Large Surfaces", 2011 BEST FEST Poster Presentation, September 2011.
63. T. Lewis, "Wave Energy Converter with Wideband Power Absorption", ECCE, Sept. 2011.
64. T. Lewis, "Per-Unit Wave Energy Converter System Analysis", ECCE, Sept. 2011.
65. A. von Jouanne, OSU Wind, Wave and Energy Storage Research & Developments, National Rural Electric Cooperatives Association's (NRECA) Cooperative Research Network (CRN), Nov. 9th, 2011.
66. T. Brekken, Presentation of "Monte Carlo analysis of the impacts of high renewable power penetration," at ECCE 2011 in Phoenix, AZ, Sep. 2011.
67. B. Batten, "Northwest National Marine Renewable Energy Center", Panelist, EnergyOcean, Portland, ME, June 2011.
68. T. Brekken, Presentation of "On Model Predictive Control for a Point Absorber Wave Energy Converter," at PowerTech 2011 in Trondheim, Norway, June 2011.
69. M. Kawase, and M. Gedney, On the use of numerical models of regional marine hydrodynamics in tidal energy, Oral Presentation, AGU Fall Meeting 2011, San Francisco, California, December 9, 2011 (invited).
70. S. Henkel, Heceta Head Coastal Conference: Florence, Oregon - Assessment of Benthic Habitats and Communities in Areas Targeted for Offshore Wave Energy Development. October 29, 2011.
71. S. Henkel, Research at the Intersection of Marine/Hydrokinetic Energy and the Environment, NSF-funded workshop: University of Minnesota, St. Anthony Falls Lab, Invited speaker: "Identifying Spatial and Temporal Patterns in Potentially Impacted Environmental Parameters", Minneapolis, MN, October 5-7, 2011.

72. S. Henkel, American Fisheries Society: Seattle, Washington - Assessment of Benthic Habitats and Communities in Areas Targeted for Offshore Wave Energy Development, Sept. 6, 2011.
73. S. Henkel, Ocean Renewable Energy Conference: Portland, OR - Priority Environmental Monitoring for Offshore Renewable Energy, August 4, 2011.
74. S. Henkel, Advanced Marine Renewable Energy Instrumentation Experts Workshop: Invited Speaker: “Surveying Benthic Habitats and Biological Communities in Areas Targeted for Offshore Wave Energy Development.” Golden, CO, April 7, 2011.
75. S. Henkel, Western Society of Naturalists: Vancouver, Washington – Spatial and Temporal Patterns in the Distribution of Infaunal Invertebrates, November 2011.
76. S. Henkel, Benthic Ecology Meeting: Mobile, Alabama – Benthic Assemblages at Sites Proposed for Wave Energy Testing, March 18, 2011.
77. J. Thomson, Panelist, Washington Ocean Energy Conference, 2011.
78. J. Thomson, COSEE Community College Faculty Summer Teaching Institute, 2011.
79. J. Thomson, Institute for Journalism and Natural Resources, 2011.
80. E. Amon, Advanced Marine Renewable Energy Instrumentation Experts Workshop, National Renewable Energy Laboratory, Presented: “Power Analysis and Data Acquisition Systems for MHK Device Testing.” Golden, CO, April 5-8, 2011.
81. A. Alberto, “Numerical simulation of a cross flow Marine Hydrokinetic turbine.” APS 64th DFD Meeting. Baltimore, MD. USA. November 20-22, 2011.
82. B. Polagye, “Estimating Marine Mammal Response to Noise from a Tidal Energy Project”, DOE Environmental Webinar, December 14, 2011.
83. B. Polagye, “Towards sustainable pathways for tidal hydrokinetic energy”, Northwest Straits Initiative 13th annual marine resource council conference, Port Townsend, WA, December 2, 2011.
84. B. Polagye, “Hydrokinetic energy research and development”, (keynote), Alaska hydrokinetics technical conference, Anchorage, AK, October 26, 2011.
85. B. Polagye, “Marine and hydrokinetic energy R&D from a national perspective”. FutureEnergy conference, Seattle, WA, October 19, 2011.
86. B. Polagye, “Developing monitoring capabilities for tidal hydrokinetic energy installations”. NSF Workshop: Research at the interface of marine/hydrokinetic energy and the environment, Minneapolis, MN, October 6, 2011.
87. B. Polagye, “Passive acoustic monitoring for tidal energy projects”, National Renewable Energy Laboratory Advanced marine renewable energy instrumentation experts workshop, Broomfield, CO, April 5-7, 2011, with C. Bassett and J. Thomson.
88. A. Alberto, “Numerical Simulations of Marine Hydrokinetic (MHK) Turbines Using the Blade Element Momentum Theory.” APS 64th DFD Meeting, Baltimore, MD. USA. November 20-22, 2011.
89. A. Schultz, Speaker at National Renewable Energy Laboratory Instrumentation Workshop, Broomfield, CO, 2011.
90. G. Garcia, “Nearshore Wave Predictions along the Oregon and Southwest Washington Coast,” Heceta Head Coastal Conference, October, 2011.
91. H. T. Ozkan-Haller, “Nearshore Wave Predictions along the Oregon Coast,” 2011 Ocean Renewable Energy Conference, August 2011.
92. M. Haller, “Wave Energy Sites: Methods of evaluation and related research” and “Northwest National Marine Renewable Energy Center”, Taller Internacional Sobre el Estado Actual de la Investigación Científica en Energías Marinas, Pontificia Universidad Católica de Chile, Santiago, Chile, July 6-7, 2011.
93. M. Haller, “Laboratory observations of waves in the vicinity of WEC-arrays”, European Wave and Tidal Energy Conference (EWTEC 2011), September, 6, 2011.
94. J. Thomson, “Numerical Modeling of Marine Hydrokinetic Turbines”, Workshop on Marine Renewable Energy, Pontificia Universidad de Chile and Gobierno de Chile. Santiago de Chile, Chile. July 7-8, 2011.
95. A. von Jouanne, *Wave Energy Testing Facilities for Scaled Device Development*, NNMREC Day, October 1st, 2010.

96. A. von Jouanne, OSU *Wave Energy Research & Developments,* Industrial Technology Research Institute in Taiwan, April 12th, 2010.
97. A. von Jouanne, NNMREC/OSU *Wave Energy Research & Developments*, NREL (Ye Li), Feb. 23rd, 2010.
98. Kawase, M., Northwest National Marine Renewable Energy Center, Seminar given at University of Oxford Department of Engineering Science, Oxford, UK, November 23, 2009; Proudman Oceanographic Laboratory, Liverpool, UK, December 8, 2009; and Department of Civil Engineering and the Environment, University of Southampton, Southampton, UK, January 5, 2010.
99. J. Thomson, Panelist, Ocean Renewable Energy Conference V / EnergyOcean, 2010.
100. A. Yokochi, "Overview of OSU's Renewable Energy Harvesting and Integration Research" Electricidade de Portugal, December 2010.
101. A. Yokochi, "Chemical engineering approaches for energy and fluid processing" Faculdade de Engenharia da Universidade do Porto, Portugal, December 2010.
102. A.F.T. Yokochi, M. Delaney "Electrochemical Methods for Prevention of Biofouling on Large Surfaces", 2010 BEST FEST Poster Presentation, September 2010.
103. J. Thomson, Nortek User Symposium, 2010.
104. J. Thomson, Panelist, Global Marine Renewable Energy Conference, 2010.
105. J. Snyder, "Wave Energy Mobile Ocean Test Berth", Energy Ocean, June 2010.
106. B. Polagye, "Comprehensive characterization of a tidal energy site", American Geophysical Union Fall Meeting, San Francisco, CA, December 13-17, 2010, with J. Thomson and C. Bassett.
107. B. Polagye, "Passive acoustics. Renewable Ocean Energy and the Marine Environment", Palm Beach Gardens, FL, November 4-6, 2010, with C. Bassett and J. Thomson.
108. B. Polagye, "Environmental effects of tidal energy: outcomes of a scientific workshop", Renewable Ocean Energy and the Marine Environment, Palm Beach Gardens, FL, November 4-6, 2010.
109. B. Polagye, "Northwest National Marine Renewable Energy Center", Renewable Ocean Energy and the Marine Environment, Palm Beach Gardens, FL, November 4-6, 2010.
110. B. Polagye, "Environmental effects of tidal energy: Outcomes of a scientific workshop",. PICES, Portland OR, October 26-29, 2010.
111. B. Polagye, "Northwest National Marine Renewable Energy Center", HydroVision 2010, Charlotte, NC, July 28-30, 2010.
112. B. Polagye, "Northwest National Marine Renewable Energy Center", 3rd Global Marine Renewable Energy Conference, Seattle, WA, April 14-15, 2010.
113. B. Polagye, "Developing capabilities for tidal hydrokinetic blade strike monitoring", 141st Meeting of the American Fisheries Society, Seattle, WA, September 6, 2011.
114. B. Polagye, "Behavioral Response of Harbor Porpoises to Vessel Noise in a Tidal Strait", 161st Meeting of the Acoustical Society of America, Seattle, WA, May 23-27, 2011.
115. B. Polagye, "Tidal Power Development Scenarios in Puget Sound, WA", AGU Ocean Sciences, Portland, OR, February 22-26, 2010.
116. B. Polagye, "Tidal and Wave Energy", Tribal Renewable Energy Conference, University of Washington, Seattle, WA, May 11, 2010.
117. T. Brekken, "The Promise of Wave Power", American Geophysical Union in Dec. 2010. (Panel session paper, invited speaker.)
118. T. Brekken, "Ocean wave power data generation for grid integration studies" at the Power and Energy Society General Meeting, July 2010. (Panel session paper, invited speaker.)
119. T. Brekken, Tutorial presentation "Wave energy converter modeling and control," at the International Symposium on Industrial Electronics (ISIE) in Bari, Italy 2010, June 2010.
120. T. Brekken, Poster presentation of "Ocean wave energy overview and research at Oregon State," at Ocean Sciences Meeting 2010.

121. M. Kawase, Physical Oceanography in support of Tidal Energy Development, Seminar, University of Liverpool Department of Engineering, Liverpool, UK, July 7, 2010.
122. M. Kawase, Energy Conversion Device in an Energetic, Baroclinic Tidal Channel. Poster presentation, American Geophysical Union 2010 Ocean Science Meeting, Portland, OR, United States, February 22 – 26, 2010.
123. A. Alberto, "Numerical Modeling of Energy Conversion Performance and Environmental Effects of Marine Hydrokinetic Turbines." APS 63rd DFD Meeting Long Beach, CA. USA. November 21-23, 2010.
124. A. Alberto, "Numerical Modeling of Hydrokinetic Turbines and their Environmental Effects." AGU 2010 Fall Meeting. San Francisco, CA. USA. December 13-17, 2010.
125. A. Alberto, "Numerical Modeling of Tidal Turbines: Near-Wake Environmental Effects." AGU Ocean Sciences 2010, Portland, OR. USA. Feb. 22-26, 2010.
126. A. von Jouanne, Wave Energy Tutorial at IEEE ECCE, San Jose, CA, Sept. 20th, 2009.
127. A. von Jouanne, Power System Fault Studies and Protection, with an update on OSU's Wave Energy Research, ONR/NSF Workshop on Energy Systems hosted by OSU, July 24th, 2009.
128. T. Brekken, Poster presentation of "A novel maximum power point tracking algorithm for ocean wave energy devices," at Energy Conversion Congress and Exposition (ECCE), San Jose, CA, Sept., 2009.
129. T. Brekken, Presentation on wave energy to the Western Energy Institute, Sept. 2009.
130. T. Brekken, "ECCE Wave Energy Tutorial," at the Energy Conversion Congress and Exposition (ECCE), San Jose, CA, Sep. 2009.
131. Brekken, "A novel permanent magnet tubular linear generator for ocean wave energy" at Energy Conversion Congress and Exposition (ECCE), San Jose, CA, 2009.
132. T. Brekken, "Wave Energy Overview," Power Electronics and Machines in Wind Applications, University of Nebraska, Lincoln, June 2009.
133. M. Kawase, and K.M. Thyng, A Three-dimensional Hydrodynamic Model of Inland Marine Waters of Washington State, United States, for Tidal Resource and Environmental Impact Assessment, Oral presentation given at Puget Sound Modeling Open House, Seattle, WA, United States, June 4, 2009; and Eighth European Wave and Tidal Energy Conference, Uppsala, Sweden, September 7 – 10, 2009.
134. J. Thomson, Society of Naval Architects and Marine Engineers, 2009.
135. S. Yim, *Numerical Modeling and Ocean Testing of a Direct-Drive Wave Energy Device Utilizing a Permanent Magnet Linear Generator for Power Take-Off*, International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Honolulu, Hawaii, June 2009.
136. A. Alberto, "Study of the turbulent wake behind a tidal turbine through numerical simulation." APS 62nd DFD Meeting. Minneapolis, MN. USA. November 22-24, 2009.
137. M. Haller, "Some potential environmental effects of wave energy arrays", Wave Energy Roundtable, Office of U.S. Senator Jeff Merkley, Hatfield Marine Science Center, Newport, OR, May 29, 2009.

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

The collaborative siting of the Newport NETS and the first successful test represent two of NNMREC's significant accomplishments. While there are many obvious technical components of these accomplishments, there are also the societal ones. For example, executing a collaborative process for site selection, which identified and addressed stakeholder concerns early in the process rather than during the permitting process, provided a foundation for a streamlined permitting process; the NETS site and first test were permitted in six months. Stakeholders also became partners in the deployment and were able to aid in deployment tasks. They acted as stewards of the test, reporting when boaters were too close or when lights were out.

The collaborative siting process for PMEC built on NNMREC's earlier experiences in community engagement. This process 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 supportive nature of the selected community, Newport, is likely to lead to a permitting process with relatively low community conflict as the outreach and engagement piece has already been heavily invested in and conflicts have been reduced.

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

Since 2008, NNMREC has engaged with the following companies involved in marine energy:

- M^3 Technologies
- Columbia Power Technologies
- Aquamarine Power
- Neptune Power
- Ocean Power Technologies
- Principle Power

- Wave Energy Technology New Zealand
- Marine Discovery Tours
- Yaquina Bay Charters
- American Bridge Manufacturing
- Many commercial fishing businesses

An important outcome of these collaborations was that companies were informed of the best practices of outreach and engagement strategies for working with the general public and existing ocean users. Companies were able to consult with experienced outreach and engagement experts who could help design an engagement process. Companies were also connected to community leaders, stakeholder networks, and interested individuals and groups. For example, shaping the outreach and engagement strategy for Aquamarine Power, from lessons learned from previous companies and OSU's efforts, led to the hiring of a local professional and opening of a local Aquamarine Power office in Newport, OR. This allowed for continued stakeholder engagement from a trusted member of the community, thus, accelerating the trust building process with stakeholders.

As PMEC continues to develop and as device developers test at Newport NETS and PMEC, NNMREC will continue its outreach and engagements efforts. Educational signs at the sites are planned in cooperation with state agencies, educational exhibits at the HMSC visitors center will continue, and further outreach in terms of summer classes for students are among the plans. Further, Hildenbrand is taking her experiences and lessons learned to Washington SeaGrant to build the outreach and engagement strength in both NNMREC institutions.

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

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

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

OUTREACH AND ENGAGEMENT PRESENTATIONS

1. C. Bassett, "Anthropogenic Noise in Puget Sound", American Cetacean Society, May 15, 2013.
2. B. Polagye, "Environmental Research & Development in Support of Marine Renewable Energy", Snohomish Public Utility District, May 16, 2013.
3. C. Bassett, "Puget Sounds", Marker Buoy Dive Club, May 1, 2013.
4. C. Bassett, "Puget Sounds", Emerald Sea Dive Club, April 3, 2013.
5. B. Batten and S. Henkel, Ocean Energy: the Wave of the Future?, Portland Garden Club, Feb 2013.
6. B. Batten, "Ocean Testing with NNMREC", Newport Ocean Observing Conference, Newport, OR, April 2013.
7. B. Batten, Ocean Energy: the Wave of the Future?, Science Pub, Albany OR, Feb 2013.
8. B. Batten, "Wave Rider: Oregon's Role in Ocean Renewable Energy", Sierra Club, January 2013.
9. S. Moran, E. Amon, "What We Learn from Device Testing" Sustainable Energy Initiative (SEI) regular meeting. Presented: February 28, 2013.
10. J. Thomson, Santiago Times, "Tides are changing to expand renewable energy options in Chile", February 20, 2013.
11. J. Thomson, New York Times "Scientists at Work" blog, 2012-2013.
12. K. Hildenbrand, "Wave Energy in Oregon", Newport Senior Center, Lunch 'n' Learn, 2012.
13. K. Hildenbrand, "PMEC and the Site Selection Process", Ocean Policy Advisory Council, 2012
14. K. Hildenbrand, "The Art and Practice of Negotiating with Ocean Stakeholders", Oregon Wave Energy Trust Conference, Portland, OR, September 2012.
15. B. Batten, "Ocean Energy: the Wave of the Future?", Science on Tap, Newport OR, September 2012.
16. K. Hildenbrand, "Engaging Coastal Stakeholders in Wave Energy Development", Oregon Chapter of American Fisheries Society, 2012.
17. K. Hildenbrand, "NNMREC Updates and Grid Connected Site Selection Process", Lincoln County Board of Commissioners, 2012.
18. B. Batten, "Ocean Energy: the Wave of the Future?", Science Pub, Corvallis OR, June 2012.
19. K. Hildenbrand, "The Pacific Marine Energy Center and the Site Selection Process", multiple presentations to: Newport Chamber of Commerce; City of Toledo & Port of Toledo joint session; City of Reedsport; City of Coos Bay; Depoe Bay Nearshore Action Team; Southern Oregon Ocean Resource Coalition; Fishermen's Advisory Committee for Tillamook.
20. B. Batten, "Northwest National Marine Renewable Energy Center", Annual Conference of Affiliated Tribes of the Pacific NW, Lincoln City, OR, May 2012.
21. K. Hildenbrand, "NNMREC and Sea Grant's Role in Outreach and Engagement", Ocean Policy Advisory Council, 2012.
22. B. Polagye, "Tidal Energy: Research at the University of Washington", Engineering in the Desert, February 15, 2012.
23. B. Polagye, "Tidal Energy: Research at the Northwest National Marine Renewable Energy Center", Fullbright Student Visit, May 30, 2012.
24. A. von Jouanne, *OSU Wave, Wind and Energy Storage Research & Developments*, David Lavalle – Canadian Film Director of White Gold Productions Inc. for film on extreme fuels and alternative energy, March 28th, 2012.
25. A. von Jouanne, Keynote Speaker, 2012 Engineers Week Banquet, *Riding the Waves: Harnessing Ocean Wave Energy through Research, Development and Testing*, Feb. 22nd, 2012.
26. A. von Jouanne, A.C. Gilbert's Discovery Village Children's Museum Science Festival, *Riding the Waves: Harnessing Ocean Wave Energy through Research, Development and Testing*, Feb. 18th, 2012.
27. A. von Jouanne, "Advanced Life Extending Control of Multiple Energy Storage Solutions to Reduce Load-Following Dependency and Wear on the Hydro-Power System", BPA Technology Innovation Summit, Portland, OR, Jan. 31st, 2012.

28. A. von Jouanne, Keynote Speaker, 2012 Engineers Week Banquet, Riding the Waves: Harnessing Ocean Wave Energy through Research, Development and Testing, Feb. 22nd, 2012.
29. A. von Jouanne, A.C. Gilbert's Discovery Village Children's Museum Science Festival, Riding the Waves: Harnessing Ocean Wave Energy through Research, Development and Testing, Feb. 18th, 2012.
30. A. von Jouanne, "Advanced Life Extending Control of Multiple Energy Storage Solutions to Reduce Load-Following Dependency and Wear on the Hydro-Power System", BPA Technology Innovation Summit, Portland, OR, Jan. 31st, 2012.
31. M. Kawaske, Tidal Energy: Research at the Northwest National Marine Renewable Energy Center, Public outreach talk, West Seattle Lions Club, May 31, 2012.
32. J. Thomson, AGU online research highlight and blog post, Fall 2012.
33. K. Hildenbrand, "Human Dimensions, Education, and Outreach in the NNMREC" Northwest National Marine Renewable Energy Center, joint university and agency PI meeting, 2011
34. K. Hildenbrand, "Wave Energy in Oregon" Tillamook Watershed Council, 2011.
35. A. von Jouanne, *Riding the Waves: Ocean Wave Energy Research in Oregon*, Oregon People's Utility District Association (OPUDA Conf.), hosted by CLPUD, Yachats, OR, Oct. 21st, 2011.
36. A. von Jouanne, Portland Monthly and OMSI "Brainstorm" Science Pub Presentation on Wave Energy, Portland, OR, Oct. 10th, 2011.
37. K. Hildenbrand, "Catching Fishermen – engaging coastal communities in wave energy development" Coastal and Estuarine Research Federation and Renewable Energy and the Ocean Environment Conference, 2011.
38. A. von Jouanne, *OSU Wave Energy Research & Developments*, Chuck Kleeschulte, Minority Staff of Senate Energy Committee, Aug. 17th, 2011.
39. K. Hildenbrand, "Working with existing ocean users" at Pacific Northwest Economic Development Region summit wave energy panel, 2011.
40. B. Polagye, "Energy Futures of Puget Sound: Are Our Tides Part of the Solution?," Lyceum 2.0, Whidbey Island, February 16, 2011.
41. A. von Jouanne, "*Overview of Wave Energy Research & Developments",* Leadership America Conf., (involving Joan Austin), Portland, OR, June 14th, 2011.
42. T. Brekken, Science Pub presentation on wave energy, Bend, Jan. 2011.
43. A. von Jouanne (with T. Brekken), NNMREC/OSU *Wave Energy Research & Developments*, Green Economy Filming, Dec. 1st, 2010.
44. K. Hildenbrand, "Public Education and Community Engagement – Making NNMREC more than an Acronym" Northwest National Marine Renewable Energy Center, joint university and agency Principal Investigator (PI) meeting, 2010.
45. K. Hildenbrand, "Lessons Learned from Reedsport" Ocean Renewable Energy Conference, September 2010.
46. K. Hildenbrand, "Public Acceptance and Community Engagement" Global Marine Renewable Energy Conference, 2010.
47. A. von Jouanne, NNMREC/OSU *Wave Energy Research & Developments*, Achievement Rewards for College Scientists (ARCS) Chapter, April 7th, 2010.
48. K. Hildenbrand, "Catching Fishermen – Engaging the Coastal Community in Wave Energy Development" Renewable Energy and the Ocean Environment Conference, 2010.
49. K. Hildenbrand, NNMREC and the NEPA process presented to Confederated Tribes of Siletz Indians, 2010.
50. M. Haller, "The Northwest National Marine Renewable Energy Center", Kwandong University, Korea, Nov. 9, 2010.
51. A. von Jouanne, OSU *Wave Energy Research & Developments*, Consumer-owned utilities, (Consumers Power, Salem Electric, Lane Electric, Tillamook PUD, Umatilla), June 11th, 2009.
52. A. von Jouanne, *Wave Energy Research & Developments*, Oregon Society of Professional Engineers Conf., May 14th, 2009.
53. T. Brekken, Da Vinci Days presentation on wave energy, July 2009.

54. K. Hildenbrand, "Wave Energy in Oregon" Newport Senior Center, 2009.
55. K. Hildenbrand, "Wave Energy in Lincoln County" Newport Chamber of Commerce, 2009.
56. K. Hildenbrand and D. Allen, "Territorial Sea Plan Amendment Process for Marine Renewable Energy" Newport City Council, 2009.
57. K. Hildenbrand, "Wave Energy in Oregon and the Territorial Sea Amendment Process" Port of Bandon Commission
58. K. Hildenbrand and D. Allen, "Territorial Sea Plan Amendment Process for Marine Renewable Energy" Yachats City Council, 2009.
59. K. Hildenbrand, "Wave Energy in Oregon" Coastal Zone Conference, 2009.
60. K. Hildenbrand, "Engaging Fishermen in Marine Renewable Energy" Coastal Zone Conference, 2009.
61. K. Hildenbrand and D. Allen, "Territorial Sea Plan Amendment Process for Marine Renewable Energy" Port of Umpqua Commission, 2009.
62. K. Hildenbrand and S. Henkel, "Wave Energy in Lincoln County", Toledo Rotary.
63. K. Hildenbrand, "Coastal Community Perspectives on Off-shore Energy Development" Oregon Chapter of the Wildlife Society, 2009.
64. K. Hildenbrand, "Wave Energy in Oregon" Coastal Zone Conference, 2009.
65. K. Hildenbrand, "Engaging Fisherman in Marine Renewable Energy" Coastal Zone Conference, 2009.
66. T. Brekken, Presentation for GECO Climate Change Talks, May 2009.
67. T. Brekken, Presentation for Association for Lifelong Learning, Feb. 2009.
68. T. Brekken, Presentation on wave energy to Sustainability Project at Clackamas College, May 5, 2009.
69. T. Brekken, Wave energy presentation for the Straub Environmental Learning Center Lecture Series, Portland, Mar. 2009.
70. T. Brekken, Presentation on wave energy to Destination OSU event in Palm Springs, CA, Mar. 3, 2009.
71. J. Thomson and B. Polagye, Pacific Science Center Science Cafe with KCTS public television, 2009.

OTHER OUTREACH ACTIVITIES

- More than one hundred tours and presentations given to Federal and State Legislators, community groups, schools, public at large (complete list to be included in final report at the end of funding period)
- More than fifty interviews given to national media outlets, including newspapers, journals, television and radio
- Monthly meetings with the Fisherman Involved in Natural Energy (FINE), Newport Oregon
- Numerous outreach meetings to communities and territorial sea planning committees about PMEC siting

LESSONS LEARNED

In this section, a selection of "lessons learned" as reported by faculty is included. These lessons will inform future NNMREC research efforts.

On working with and being relevant to the industry: The technology around harnessing wave and tidal energy is still in a research and development phase, undergoing rapid growth and evolution. It has been satisfying to observe instances in which NNMREC's research directly affects the industry, and faculty find the immediate demand for and relevance of their research to be professionally rewarding. NNMREC's approach of remaining in close contact with industrial partners, for example Columbia Power Technologies M3, or Ocean Renewable Power Company, ensures that NNMREC's research is immediately relevant to them. This parallels NNMREC's collaborative approach to working with regulatory and resource agencies discussed in the previous section. Finally, the strong ties to the scientific community and its extensions (e.g. National Academy of Science) helps to solidify NNMREC's position at the edge of scientific discovery. This multi-pronged approach results in a Center that will remain critically relevant to advancing MHK technology.

On methodology development vs. tool development: The development of methodologies and procedures can be more important than the development of tools, due to the fast-moving nature of software. However, open-source tools that can be modified by industry for specific applications have increased the relevance and impact of NNMREC's research and led to a number of research collaborations. Software tools and programs can become obsolete without intensive updating and maintenance – the time required for this should not be underestimated.

On access to experimental and field data: While essential for verification and validation of numerical simulations, experimental data is scarce and difficult to obtain. There continues to be a very limited number of datasets in the open literature that can be used to validate and develop models for MHK devices and no data sets exist from full-scale field testing. This is a critical gap since computational models are playing an ever-increasing role in the industry, refining designs for performance and minimizing environmental effects. Obtaining scaled experimental measurements is an essential, intermediate step before full scale, field data becomes available. To accelerate the industry's maturation process, support is necessary to provide this information and develop computational tools that are adequate in cost, turn-around time, and complexity/user expertise for industrial use in structural design and optimization.

On uncertainty in regional-scale numerical models: Simulation of energy harvesting by large arrays of MHK devices and the consequences on regional hydrodynamics and wave climates often represents a novel application of such modeling techniques. For example, Kawase's simulations of limited domain and boundary conditions demonstrated that these factors can produce large, quantitative uncertainty in model results. Regional numerical models are useful and will play a vital role in assisting with MHK development, but care and thoughts must go into understanding their limitations.

On deploying instrumentation: Any instrumentation deployment in harsh wave and tidal environments entails significant risk. Risk can be mitigated through incremental development and testing in both the laboratory and progressively more intense field conditions. For example, project schedules should accommodate at least two weeks of laboratory bench testing with all instruments and sensors attached prior to deployment. This allows for measurement of the total system power draw, data file size estimation per hour, and all aspects of the software and data acquisition system to be tested. Reconfiguration in the field is always more expensive than bench testing and may not be possible without instrument retrieval for autonomous packages. The acquisition of turbulence data from tidal energy sites involved a progression from a large, rigid frame in a moderately energetic environment (2 m/s peak velocity) to a short-term, compliantly moored package in a more energetic environment (2.5 m/s peak velocity) to a longer-term deployment in a fully energetic environment (greater than 3 m/s peak velocity). This progression allowed refinement to both the instrumentation configuration (Doppler velocimeters) and mooring arrangement through intermediate testing phases. This progression for instrumentation parallels best practices for MHK device development.

On environmental monitoring of MHK devices: In order to get data around an "active" WEC, vigorous sea states are needed. This presents a challenge for vessel-based operations and drives observations toward remote monitoring or autonomous instrumentation packages deployed in close proximity to the WEC. The strong currents around TECs create similar operational challenges. For example, pelagic trawls, which are convention approach to fisheries sampling are ineffective during the periods of strongest currents when information about fisheries distributions is of greatest interest. However, mooring passive acoustic instruments can be ineffective during periods of strong currents due to sound from self-noise (turbulence) or sediment generated noise. Consequently, drifting acoustic measurements are a recommended best practice for both WECs and TECs.

On EMF monitoring of wave converters: In order to fully characterize the EMFs from an energized WEC, it is necessary to monitor the WEC while it experiences a wide variety of sea states, oceanographic current conditions, and meteorological conditions. So in addition to measuring the EMFs for short periods of time over a fine grid of survey locations (to characterize the directional nature of EMF propagation from the EMF emitting source), it is also necessary to place the EMF sensor package on the seafloor, for an extended period of time (weeks to months), as close to the emission source as possible, and monitor the output as received at that location. It is also necessary to measure the electric current output waveforms directly from the WEC prior to power conversion, since these are the non-stationary waveforms (typically a low-pass, phase-lagged version of the ocean surface wave and swell waveforms) associated with primary EMF emission. Power conversion may also result in powerline frequencies and their harmonics. These can be difficult measurements to obtain, but are necessary to accurately characterize WEC EMF.

On outreach and engagement: Purposeful outreach and engagement and collaborative community processes are critical to advancing marine energy projects. Resources must be included in developer plans and budgets to inform and engage the general public on projects in their waters. For example, the public wants to know about EMF work, acoustics, marine mammal observations, and how benthic habitats are affected, as well as simply wanting to know, "what's that thing out there?"

PATENTS

- "Methods And Apparatus For Power Generation", Rhinefrank, K.; von Jouanne, A.; Prudell, J.; Schacher, A.; Yokochi, A.F.T.; Brekken, T.; Elwood, D.; Stillinger, C.; Paasch, R. K. PCT/US2008/002837.
- "Magnetic Helical Screw Drive" Rhinefrank; K.; Yokochi; A.F.T.; von Jouanne; A.; Dittrich; M.; Agamloh; E. PCT/US2009/0251258.
- "A Heave-plate mooring for wave energy conversion via changing loads", J. Thomson, J. Talbert, A. deklerk; provisional patent application number 61/664,444; docket number OSC-P016P, 2013.

REFERENCE MODEL EFFORT

NNMREC faculty and graduate students have assisted with the development of wave and current reference models.

Wave Reference Model

T. Brekken directed masters student Kelley Ruehl to develop a model of a hydraulic based power take off system for a point absorber wave energy converter. This model was used to develop estimates of power take off efficiency as a function of wave climate. The work was funded by Sandia National Laboratories.

Tidal Current Reference Model

B. Polagye provided the reference resource for the Tidal Current Reference Model (RM 1). This was based on a comprehensive synthesis of tidal current measurements at sites throughout Puget Sound and produced a reference velocity distribution that could be extrapolated to different depths, as well as sites with stronger or weaker peak currents. M. Kawase provided input on the simulation of RM 1 in SNL-EFDC and J. Thomson contributed an analysis of turbulence to inform peak load design conditions for the turbine blades.

While not involved with the development of RM 1, A. Aliseda's group has made use of the scale-model geometry to conduct computational analysis and experimental studies of turbine wake interactions.

A. Aliseda and B. Polagye are members of the scale-model working group that has grown out of the Reference Model effort. This working group meets twice-monthly to discuss recent experimental results and coordinate methodology to allow for direct comparison of experimental results by different groups. Both axial flow and cross flow turbines are included within the group's scope.

GRADUATED STUDENTS

Student	Research Title	Current Employment
Ph.D.		
Amon, Ean Electrical Engineering, OSU	Development of Control Topologies for Ocean Wave Energy Devices Utilizing a Novel Power Analysis and Data Acquisition System (2010)	Oregon State University/ NNMREC
Polagye, Brian Mechanical Engineering, UW	Hydrodynamic Effects if Kinetic Power Extraction by In-Stream Turbines (2009)	University of Washington/NNMREC
Stillinger, Chad Electrical Engineering, OSU	On the Study of WEC Prototype Advancement with Consideration of Real-Time Life Extending Control (2011)	Oregon Institute of Technology
Thyng, Kristen Mechanical Engineering, UW	Numerical Simulation of Admiralty Inlet, WA, with Tidal Hydrokinetic Turbine Siting Application	Texas A&M University
M.S.		
Adamski, Samantha Mechanical Engineering, UW	Numerical Modeling of the Effects of a Free Surface on the Operating Characteristics of Marine Hydrokinetic Turbines (2013)	Newport Engineering (US Navy) Bremerton, WA
Brown, Nicholas Civil Engineering, OSU	Experiments on the Accuracy of a 3D Motion Capture System (2010)	Ocean Facilities Program, US Navy, Port Huename, CA
Delaney, Matthew Chemical Engineering, OSU	Study of Graphite-Polyurethane Composite Thin Film Electrodes for Their Use in Electrochemical Antifouling Systems (2011)	Sandia National Laboratory
DuBuque, Geoffrey Mechanical Engineering, UW	A Lumped Parameter Equilibrium Model of a Submerged Body with Mooring Lines (2011)	Boeing
Epler, Jeff Mechanical Engineering, UW	Tidal Resource Characterization from Acoustic Doppler Current Profilers (2010)	Williamson & Associates (maritime construction)
Gooch, Sam Mechanical Engineering, UW	Tidal Site Characterization (2009)	DNV
Guo, Yisen Civil Engineering, OSU	Numerical Modeling and Analysis of WEC Experiments	University of Kentucky
Graber, Joe Mechanical Engineering, UW	Infrared Monitoring at MHK Sites (2011)	Edmonds Community College
Hall, Taylor Mechanical Engineering, UW	Numerical Simulation of a Cross-Flow Marine Hydrokinetic Turbine: Blade Dynamics and Energy Extraction (2012)	Battelle Memorial Institute
Honneger, David Civil Engineering, OSU	Partially supported by NNMREC; moved onto a different research project	Oregon State University, PhD Student
Hovland, Justin Mechanical Engineering, OSU	Predicting Deep Water Breaking Wave Severity (2010)	Oregon Iron Works
Javaherchi, Teymour Mechanical Engineering, UW	Fluid Dynamics of Tidal Turbines: The Near Wake Region (2010)	University of Washington, PhD student
Kassem, Sarah Ocean Engineering, OSU	Wave Modeling at the Mouth of the Columbia River (2010)	H. R. Wallingford, Oxford, UK
Lenee-Bluhm, Pukha Mechanical Engineering, OSU	The Wave Energy Resource of the US Pacific Northwest (2010)	Columbia Power Technologies
McArthur, Shaun Electrical Engineering, OSU	Residential Load Simulation and Applied Load Management Strategies (2011)	Unknown
McNatt, Cameron	Wave Field Patterns Generated by Wave Energy	University of Edinburgh,

Ocean Engineering, OSU	Converters (2012)	PhD Student
Meicke, Steven Mechanical Engineering, OSU	Hydroelastic Modeling of a Wave Energy Converter using the Arbitrary Lagrangian-Eulerian Finite Element Method in LS-DYNA (2012)	HDR
Moon, Ruby Public Policy, OSU	IDA Framework to Examine the Relationship Between Regulating Enforcers and the Commercial Trawl Fishery of Newport, Oregon (2012)	Seeking Employment
Niblick, Adam Mechanical Engineering, UW	Experimental and Analytical Study of Helical Cross-Flow Turbines for a Tidal Micropower Generation System (2012)	Creare, Inc.
Ogg, Anderson Lt. Mechanical Engineering, UW	Screening Tests of Composites for use in Tidal Energy Devices (2011)	Naval Architecture Marine Engineering, U. S. Coast Guard Academy
Okuda, Jeremy Electrical Engineering, OSU	Micro In-lab Grid Integration of a Wave Energy Converter (2011)	Bonneville Power Administration
Oskamp, Jeffrey Ocean Engineering, OSU	Toward Wave Energy in Oregon: Predicting Wave Conditions and Extracted Power (2011)	Engineer for Paul C. Rizzo Associates
Palodichuk, Michael Mechanical Engineering, UW	Tidal Resource Mapping (2012)	ATA Engineering
Porter, Aaron Civil Engineering, OSU	Laboratory Observations and Numerical Modeling of the Effects of an Array of Wave Energy Converters (2012)	Coast & Harbor Engineering, Edmond, WA
Ruehl, Kelley Mechanical Engineering, OSU	Time-Domain Modeling of Heaving Point Absorber Wave Energy Converters, Including Power Take-Off and Mooring (2011)	Sandia National Laboratories
York, Charles Electrical Engineering, OSU	Modeling and Experimental Verification of Electric and Magnetic Fields Generated by Undersea Power Transmission cables (2010)	Bonneville Power Administration
B.S.		
Beba, Tricia	An Investigation of Turbine Depth on Device Performance in a Sheared Flow (2011)	Formerly of DNV KEMA Inc. (a wind energy company)

CURRENT STUDENTS

Student	Research	Defense
Ph. D.		
Bassett, Chris Mechanical Engineering, UW	Underwater Noise at Tidal Energy Sites	Summer 2013
Bosma, Bret Electrical Engineering, OSU	A Design Guide for Wave Energy Developers	Summer 2013
Bunn, Malachi Chemical Engineering, OSU	Development and Validation of an Electrochemical Reaction/Diffusion/Convection Model for the Electrochemical Biofouling Protection of Surfaces	Summer 2014
Brown, Adam Mechanical Engineering, OSU	On the Effects of Breaking Waves on Deep Water Wave Energy Converters	Spring 2014
Cavagnaro, Rob Mechanical Engineering, UW	Performance and Control of Cross Flow Turbines	Winter 2016
Davis, Andrew Mechanical Engineering, OSU	Dynamic Modeling and Control of WEC Mooring Systems	Spring 2015
Fry, Brady	Systems Design and Integration of EM Sensor	Spring 2013

Oceanography, OSU	Platforms	
Javaherchi, Teymour Mechanical Engineering, UW	Fluid Dynamics of Tidal Turbines: The Near Wake Region	Summer 2013
Joslin, James Mechanical Engineering, UW	Design of Monitoring and Maintenance Systems for Marine Renewable Energy Development	Spring 2015
Lettenmaier, Terry Electrical Engineering, OSU	Testing of Wave Energy Converters using the Ocean Sentinel Instrumentation Buoy	Spring 2013
Lewis, Tim Electrical Engineering, OSU	Design and Control of an Autonomous Two-Body Wave Energy Converter for maximum Power Absorbtion	Summer 2013
Lou, Junhui Civil Engineering, OSU	Numerical Modeling and Experimental Calibration of Wave Energy Converter Analysis and Design	Spring 2014
Sale, Daniel Mechanical Engineering, OSU	Computational Methods for Optimal Design of Marine Hydrokinetic Turbines: Structural Composites and Hydrodynamics	Spring 2014
Zhang, Yi Civil Engineering, OSU	Numerical Modeling of Coupled Fluid-Structure Interaction and Large-Scale Experiments of WEC	Winter 2014
M.S.		
Biligiri, Kaushal Electrical Engineering, OSU	Grid Emulator Project	Spring 2013
Boren, Blake Mechanical Engineering, OSU	Modeling and Control of Horizontal Pendulum Wave Energy Converters	Spring 2013
Black, Colleen Civil Engineering, OSU	Wave Scattering in the Near-field of a WEC-array via Stereo Video Measurements	Spring 2014
Casey, Sean Mechanical Engineering, OSU	Comparison of passive and active controlled hydraulic power take off systems for wave energy conversion	Spring 2013
Collins, Erin Mechanical Engineering, OSU	Sustainability Analysis and Design for a Point Observer Mooring System	Spring 2014
Deppe, Walt Mechanical Engineering UW	Measurements of Dissolved Oxygen in a Tidal Strait	Winter 2014
Hunyh, Kristina Mechanical Engineering, UW	Simulation of Estuarine Dynamics	Spring 2013
Merritt, Joshua Mechanical Engineering, OSU	Modeling and Control of a Floating PTO Wave Energy Converter	Spring 2013
Nichol, Tyler Mechanical Engineering, UW	Dynamic Modeling of Slack Moored Tidal Turbines	Spring 2013
Odea, Annika Civil Engineering, OSU	Nearshore Effects of WEC-arrays at Oregon Coastal Sites	Spring 2014
Stelzenmuller, NIck Mechanical Engineering, UW	Experimental Flume Testing of an Array of Scale MHK DOE Reference Model 1 Turbines	Spring 2013
B.S.		
Freund, Elizabeth Chemical Engineering, OSU	Evaluation of Electrochemical Biofouling Prevention of Transparent Conductive Oxide Films in Seawater	Spring 2013
Gedney, Marisa Oceanography, UW	Senior Project: Mesoscale Eddies and Currents around Axial Seamount	Spring 2013
Hunyh, Kristina Mechanical Engineering, UW		Spring 2013
Nichol, Tyler Bioengineering, UW	Dynamic Modeling of Slack Moored Tidal Turbines	Spring 2013

COLLABORATIONS

MHK DEVELOPERS

- Aquamarine Power
- Columbia Power Technologies
- M3 Wave, LLC
- Ocean Power Technologies
- Ocean Renewable Power Corporation
- OpenHydro
- Oscilla Power
- Neptune Wave Power
- Principle Power
- Shift Power Solutions
- WET-NZ/IRL/NWEI
- Verdant Power

INDUSTRY CONSULTANTS

- AXYS Technologies
- 3U Technologies
- Pacific Energy Ventures
- Sound & Sea Technologies
- SAIC

MARITIME/MANUFACTURING SERVICE PROVIDERS

Dozens of Local Service Providers; including the following:

- Halco Manufacturing
- Englund Marine
- ESI Motion
- GEO Space
- Marine Discovery Tours
- MacArtney
- Ocean Innovation
- PMI
- Port of Toledo
- Port of Newport
- SAAB SeaEye
- SeaView Systems
- TRI-AGG Inc.
- Yaquina Bay Charters
- Wiggins Tug & Barge, & NRC Environmental

NATIONAL LAB COLLABORATIONS

- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratories-

DOMESTIC UNIVERSITY COLLABORATIONS

- Texas A&M University
- University of California Irvine
- University of Colorado
- University of Hawaii
- University of Maine
- University of New Hampshire

INTERNATIONAL UNIVERSITY COLLABORATIONS

- Cranfield University, UK
- Fraunhofer-Institut für Windenergie und Energiesystemtechnik
- Imperial College London
- Irish Marine and Energy Resource Cluster (IMERC)
- Kwandong University, Korea
- Plymouth University
- Pontificia Universidad de Catholica, Santiago, Chile
- UK Engineering and Physical Science Research Council (EPSRC)
- University of Edinburgh

OTHER COLLABORATIONS

- Central Lincoln PUD
- Flora Family Foundation
  Oregon Coast Aquarium
- Oregon Wave Energy Trust (OWET)
- Economic Development Alliance of Lincoln County
- European Marine Energy Centre (EMEC)
- NAVFAC
- Northern Wasco County PUD
- Oregon Wave Energy Trust
- S. A. Hempel
- Seabird Electronics
- Snohomish PUD