Marine and Hydrokinetic Technology (MHK) Instrumentation, Measurement, and Computer Modeling Workshop

W. Musial, M. Lawson, and S. Rooney
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5000-57605
February 2013

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

Marine and Hydrokinetic Technology (MHK) Instrumentation, Measurement, and Computer Modeling Workshop

W. Musial, M. Lawson, and S. Rooney
National Renewable Energy Laboratory

Prepared under Task No. WA09.3406

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5000-57605
February 2013

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Acknowledgments

Thank you to all the session chairs and invited speakers who participated in the MHK Instrumentation, Measurement, and Computer Modeling Workshop. Their insights and willingness to share their experiences developing marine energy technologies helped make the workshop a success. In addition, we would like to thank the note takers, Christopher McComb, Adam Nelessen, Daniel Houck, and Richard Meier, who did an excellent job documenting the proceedings of the facilitated discussion sessions. Finally, we would like to acknowledge the U.S. Department of Energy for providing the funding and support that enabled this workshop.

Acronyms

MHK	Marine and hydrokinetic
EC	Wave energy converter
IEC	International Electrotechnical Commission
EMEC	European Marine Energy Center
PTO	Power take off
COE	Cost of energy
RAO	Response amplitude operator
TRL	Technology Readiness Level
NDA	Nondisclosure agreement
CRADA	Cooperative research and development agreement
OC3 and OC4	Offshore codes comparison 3 and 4
O&M	Operation and maintenance
SNMREC	Southeast National Marine Renewable Energy Center
NNMREC	Northwest National Marine Renewable Energy Center

Executive Summary

The Marine and Hydrokinetic Technology (MHK) Instrumentation, Measurement, and Computer Modeling Workshop was hosted by the National Renewable Energy Laboratory (NREL) in Broomfield, Colorado, July 9–10, 2012. The workshop brought together over 60 experts in marine energy technologies to disseminate technical information to the marine energy community, and to collect information to help identify ways in which the development of a commercially viable marine energy industry can be accelerated.

The workshop was comprised of plenary sessions that reviewed the state of the marine energy industry and technical sessions that covered specific topics of relevance. Each session consisted of presentations, followed by facilitated discussions. During the facilitated discussions, the session chairs posed several prepared questions to the presenters and audience to encourage communication and the exchange of ideas between technical experts. Following the workshop, attendees were asked to provide written feedback on their takeaways from the workshop and their best ideas on how to accelerate the pace of marine energy technology development.

The first four sections of this document give a general overview of the workshop format, provide presentation abstracts, supply discussion session notes, and list responses to the post-workshop questions. The final section presents key findings and conclusions from the workshop that suggest what the most pressing MHK technology needs are and how the U.S. Department of Energy (DOE) and national laboratory resources can be utilized to assist the marine energy industry in the most effective manner.

Table of Contents

Acknowledgments ..... **iii**
Acronyms ..... **iv**
Executive Summary ..... **v**
Table of Contents ..... **vi**
1 Introduction **1**
1.1 Objectives 1
1.2 Report Framework 1
2 Workshop Description **2**
3 Facilitated Discussion Sessions **3**
4 Post-Workshop Questions **4**
5 Key Findings and Conclusions **5**
5.1 What Are the Most Important Actions That Can Be Taken to Advance the Marine Energy Industry and What Role Should DOE and the National Labs Play? 5
5.2 Technology and Research Area-Specific Takeaways 6
5.3 How Can Future Events of a Similar Nature Be Improved? 8
Appendix A: List of Workshop Attendees **9**
Appendix B: Workshop Agenda **11**
Appendix C: Workshop Presentations **17**
Plenary Session 17
Instrumentation and Testing 19
Modeling 24
Appendix D: Notes from Facilitated Discussion Sessions **29**
Day 1: Plenary Session Discussion 29
Testing Track 31
Modeling Track 35
Day 2: Open Discussion of Industry Needs, Workshop Findings, and Closeout 37
Appendix E: Responses to Post-Workshop Questions **40**

1 Introduction

A wide spectrum of marine and hydrokinetic technologies are being developed by industry, universities, and national laboratories in the United States and around the globe. Experience gained in the development of renewable energy, aerospace, and automotive technologies shows that sharing and disseminating technical expertise accelerates the pace of technology development and rapidly progresses the industry towards commercial viability. For this exact purpose, the National Renewable Energy Laboratory organized the Marine and Hydrokinetic Technology (MHK) Instrumentation, Measurement, and Computer Modeling Workshop to bring together technical experts from industry, national laboratories, and academia. The workshop goals were to disseminate technical information regarding environmental monitoring, instrumentation and measurements, and computer modeling to the marine energy community, and to collect information to help identify ways to accelerate the development of a commercially viable marine energy industry.

1.1 Objectives

The objectives of the workshop were to:

- Share the latest relevant knowledge among technical experts
- Review relevant state-of-the-art field measurement technologies and methods
- Review cutting-edge numerical modeling techniques
- Examine lessons learned during the development of the wind industry and review experience gained during recent MHK field deployments
- Identify major gaps in modeling and instrumentation capabilities
- Provide a forum for stakeholders to elicit substantive input for the development of new marine energy field-deployable instrumentation packages
- Solicit and discuss impediments to and ways to accelerate MHK commercial viability.

1.2 Report Framework

The remainder of this document describes the proceedings of the workshop. First, a general description of the workshop is given, followed by a summary of the discussion that followed each workshop session. Next, the post-workshop questions that were answered by attendees are presented. Finally, the conclusions and common themes from the presentations, discussion sessions, and post-workshop questions are addressed in the Key Findings and Conclusions section. For completeness, presentations that were given at the workshop are available at http://www.nrel.gov/water/workshop_mhk_2012.html.

2 Workshop Description

Over 60 technical experts from the wind industry, national laboratories, and academia attended the MHK workshop (see Appendix A). The workshop attendance was intentionally kept small to encourage open and in-depth discussion between subject matter experts, thus facilitating the exchange of ideas on how to advance the marine measurement systems, what computer-based modeling tools are needed to accelerate MHK technology development, and how to satisfy environmental modeling and permitting concerns. Prior to arriving, attendees were informed that the workshop was not a venue to market or advertise products, programs, or facilities.

The 2-day workshop was comprised of general plenary and focused technology sessions (see agenda in Appendix B). The plenary session included presentations to provide an overview of the current state of the MHK industry in terms of environmental monitoring, data collection, experimental testing, and numerical modeling. In addition, the following focused technology sessions were held in parallel:

- Testing and Instrumentation
- Numerical and Analytical Modeling.

These sessions were intended to provide a detailed understanding of cutting-edge marine energy technologies and to identify gaps in current experimental and numerical capabilities.

All sessions were led by a session chair, with a panel of experts delivering individual 20-minute presentations. Appendix C lists the presentations and provides the presentation abstracts. In addition, a plenary discussion session was held at the end of each workshop to identify industry needs. Facilitated discussion sessions that addressed the questions presented in Appendix B were held following each session and note takers recorded the topics and conclusions.

3 Facilitated Discussion Sessions

During the discussion sessions, the chairs posed several prepared questions (see Appendix B) to the presenters and the audience. The goal of asking the questions was to encourage attendees to discuss ways to advance marine renewable technologies and to facilitate discussion on how to best allocate modeling and instrumentation resources in the future. The discussion did not always explicitly follow the question topics, however, but the chairs kept the discussion relevant to the session topic area.

NREL placed several undergraduate and graduate interns in each discussion session to document the topics discussed. Appendix D presents a lightly edited synthesis of their notes. Key conclusions from the discussion sessions are addressed further in Section 5.

4 Post-Workshop Questions

At the conclusion of the workshop, the attendees were asked to submit email responses to the following three questions:

1. What was your most significant takeaway from the workshop?
2. What is the most important thing that you think should be done to advance the marine and hydrokinetic industry? We are looking for your best "big idea" that would have a broad national impact on accelerating commercialization.
3. What should we do to improve future events of a similar nature?

Responses from attendees who submitted answers are presented in Appendix E. Key conclusions from the post-workshop question responses are discussed further in Section 5.

5 Key Findings and Conclusions

The workshop presentations, notes from the facilitated discussion sessions (Appendix D), and the responses to the post-workshop questions (Appendix E), were thoroughly reviewed to identify key findings and conclusions that can help the U.S. Department of Energy (DOE) and the national labs direct resources in a manner that best addresses the needs of the marine energy industry. For clarity, the findings and conclusions are grouped into the following categories:

- What are the most important actions that can be taken to advance the marine energy industry and what role should DOE and the national labs play?
- Technology and research area-specific takeaways:
  - Testing, instrumentation, and resource characterization
  - Numerical modeling and model verification and validation
  - Environmental monitoring and permitting
  - Wave energy conversion (WEC) devices
- How can future events of a similar nature be improved?

The remainder of this section presents these findings and conclusions in list form. Comments from the workshop organizers (NREL) are also included where appropriate.

5.1 What Are the Most Important Actions That Can Be Taken to Advance the Marine Energy Industry and What Role Should DOE and the National Labs Play?

Below are the workshop attendees' responses to the above question.

Get Devices in the Water

The best way to advance the marine energy industry is to get prototype devices in the water and see how they perform. When testing these devices, it is critical to have adequate instrumentation on the device so that when problems or failures occur, they can be studied and solutions can be developed.

Create a Large-Scale Wave and Water Current Device Test Center

Workshop attendees recommend that DOE create a large-scale test facility [similar to the European Marine Energy Center (EMEC)] in the United States, where device developers can test device prototypes. Ideally, this type of a facility would allow for streamlined environmental permitting and would provide infrastructure (e.g., power cabling) and a fully characterized wave or water current resource to defray testing costs for device developers.

Minimize the Environmental Monitoring and Permitting Burden for Device Developers

One way for DOE to accelerate the pace of marine energy technology development is to generate environmental monitoring and permitting practices that are accepted by regulatory agencies, thus making it easier for developers to rapidly field test prototype devices and deploy commercial-scale arrays.

Create a Design Reference Site Database

Many device developers and researchers feel that DOE should fund a project to characterize marine energy resources (i.e., wave and water current environments and extreme conditions) at several characteristic deployment sites to create a design reference site database. The database should be made publicly available to help engineers design devices that will perform well and survive in typical wave and current deployment sites. In addition, the database will enable national labs, academia, and DOE to identify the types of devices that are most promising at different deployment sites. This type of project would help decrease the cost of MHK devices by lowering the design uncertainty and accelerating the pace of marine energy technology development in the United States.

Develop a Turbulence Measurement Instrumentation Package

The national labs should develop a mobile instrumentation system to measure ocean, tidal, and river turbulence that can be loaned to device developers. Turbulence in the marine environment is poorly characterized, but it is thought to significantly influence hydrodynamic and structural loads. Therefore, providing the ability to easily and cost effectively measure turbulence would be very valuable to device designers.

Improve Communication Between the MHK Industry and Researchers

The U.S. MHK industry will benefit if research performed in academia and the national labs is directed towards solving relevant technological and environmental problems. Industry currently perceives a disconnect between academic research and its immediate modeling and instrumentation needs.

Compile a Listing of Available Instrumentation and Testing Facilities

Testing resources, such as wave tanks and instrumentation packages that DOE and the national labs can provide, should be compiled and posted on a website that is publicly accessible.

Reduce Cost Share Requirements for DOE Funding

Several developers expressed their opinion that the large cost-share (typically 50%) required to receive DOE funding is overly burdensome for a nascent industry. Many would prefer fewer awards with a lower cost-sharing requirement.

Facilitate the Sharing of Proprietary Data

Intellectual property is of great concern to marine energy developers because, without an income stream, it is the only way of assessing the value of some companies. The resulting tendency is to keep internal data secret to maintain a market advantage. This lack of data sharing reduces the opportunity for the entire industry to move forward. DOE could provide incentives and develop intelligent ways to encourage the sharing of data.

5.2 Technology and Research Area-Specific Takeaways

5.2.1 Testing, Instrumentation, and Resource Assessment

Instrumentation and testing methods need to be further developed to meet the needs of the marine energy community. As a result, there is a significant amount of work to be done to satisfactorily characterize inflow and wave fields, device performance, and wakes in wave tanks and the open ocean. Extensive instrumentation development and field testing is required to accomplish this.

Industry needs a way to extrapolate wave and water current data to 100-year storm events

Extreme loads drive the designs of wave and water current devices. An accepted method of extrapolating from several years of data to 100-year storm events is needed to estimate the level of robustness required in device designs.

Sensor certification is needed

Certification of sensors (similar to what is done in the wind industry) would provide investors, regulators, and device designers with confidence in wave tank and field measurements.

Scale-model testing standards are needed

A comprehensive set of scale-model testing standards are needed. If developers can demonstrate their device performance while adhering to the testing standards it will verify their results. The International Towing Tank Conference is currently developing standards that may be sufficient for this purpose.

5.2.2 Numerical Modeling and Model Verification and Validation

Challenges to and suggestions for improvement of numerical modeling techniques and verification and validation methods are described in this section.

Linear models are not always adequate

Linear modeling tools are not always adequate because many devices operate in nonlinear regimes.

A comprehensive set of model-scale tests are needed for numerical model verification and validation

To verify and validate numerical models, a detailed set of experimental data is needed. Moreover, all specification for the devices that are tested must be open source, so that modelers can simulate the exact conditions of the experiment. Experience from the wind industry and NREL's unsteady aerodynamics wind turbine experiment (the UAE) shows that a multiyear testing effort lead by the national labs is the best way to produce this data.

Open-source wave and tidal device simulation tools are not available

Open-source design tools for WEC and water current devices would reduce the cost of developing marine energy devices and benefit the marine energy industry as a whole.

5.2.3 Environmental Monitoring and Permitting

This section summarizes key findings and conclusions from discussions on the topic of environmental permitting and monitoring.

Environmental monitoring and permitting is a major barrier for the nascent wave and water current industries

The time and cost involved in environmental permitting and monitoring is a major barrier to field-testing wave and tidal devices. This barrier is slowing the pace of technology development because small companies cannot test single prototype devices in a timely and economically feasible manner.

5.2.4 WEC Devices

This section summarizes key findings and conclusions from discussions on the topic of WEC devices.

The WEC industry has yet to converge on an optimal device design

The concept devices being developed by various developers all extract energy from the wave environment in very different ways, thus suggesting that the industry has not yet converged on a consistent, optimal design.

Accurate cost-of-energy models are needed so developers can determine optimal device designs

More accurate cost models are needed for WEC devices so that economically feasible devices can be developed. Some cost model components can be borrowed from cost models developed for other industries (such as offshore wind and oil and gas).

5.3 How Can Future Events of a Similar Nature Be Improved?

Suggestions for future workshops include the following.

Separate Technical Tracks by Device Type

Many conference attendees felt that future workshops should be separated into wave and water current device sessions, as opposed to numerical modeling and measurement sessions. This would provide more of an opportunity for numerical modelers and experimentalists to interact. This interaction is needed because both groups rely on one another for information to improve numerical and experimental methods.

Focus More on Cost-of-Energy Modeling

Future workshops should have some focus on cost-of-energy modeling because developing cost-efficient devices is critical to the long-term success of the industry.

Encourage More Investor Involvement

Investors play a large role in determining the pace at which the MHK industry matures. Having investor involvement at the workshop would benefit the technical attendees by providing a perspective on what technology improvements are required to make MHK technologies more attractive to investors.

Appendix A: List of Workshop Attendees

Attendees		
Name	**Company**	**Email**
Al LiVecchi	NREL	al.livecchi@nrel.gov
Andrea Copping	Pacific Northwest National Laboratory (PNNL)	andrea.copping@pnnl.gov
Brian O'Rourke	Resolute Marine Energy Inc.	borourke@resolutemarine.com
Brooke White	U.S. Department of Energy (DOE)	brooke.white@ee.doe.gov
Bruce LeBlanc	Sandia National Laboratory (SNL)	blebla@sandia.gov
Dave Tietje	Science Applications International Corp. (SAIC)	EMIL.D.TIETJE.III@saic.com
David Oliver	Benthic GeoScience Inc.	doliver@BenthicGeo.com
Don Thompson	Cardinal Engineering	dthompson@cardinalengineeringllc.com
Ian Prowell	MMI Engineering	IProwell@MMIEngineering.com
James VanZwieten	Florida Atlantic University	jvanzwi@fau.edu
Jeff Rieks	Cardinal Engineering	jrieks@cardinalengineeringllc.com
Katherine McCaffrey	University of Colorado	klmccaffrey2@gmail.com
Kourosh Shoele	Re Vision	kourosh@re-vision.net
Marco Masciola	NREL	marco.masciola@nrel.gov
Michael Reed	DOE	michael.reed@doe.gov
Peter Hamlington	University of Colorado	Peter.Hamlington@Colorado.EDU
Renee Boileau	National Research Council Canada	Renee.Boileau@nrc-cnrc.gc.ca
Rick Driscoll	NREL	frederick.driscoll@nrel.gov
Tom Edmunds	Lawrence Livermore National Laboratory	edmunds2@llnl.gov
Tom McNulty	Garrad Hassan	Tom.McNulty@gl-garradhassan.com
Tracy Kutney	Natural Resources Canada	Tracey.Kutney@NRCan-RNCan.gc.ca
Warren Bartel	Naval Facilities Engineering Command (NAVFAC) Engineering Service Center	warren.bartel@navy.mil
Ye Li	NREL	ye.li@nrel.gov
Speakers		
Name	**Company**	**Email**
Al Schacher	Columbia Power	aschacher@columbiapwr.com
Alain Clement	ECN Centrale Nantes	alain.clement@ec-nantes.fr
Alan Turner	MicronOptics	aturner@MICRONOPTICS.COM
Allie Cribbs	Ecomerrit	acribbs@ecomerittech.com
Arnie Fontaine	Pennsylvania State University	aaf1@arl.psu.edu
Bob Thresher	NREL	robert.thresher@nrel.gov
Borna Hamedni	Ocean Power Technologies (OPT)	bhamedni@oceanpowertech.com
Brett Prairie	Rockland Scientific	brett@rocklandscientific.com
Danny Sale	University of Washington	danny@gmail.com
Dave Kring	Navatek	dkring@navatekltd.com
Diana Bull	SNL	dlbull@sandia.gov
Muhammed Ali	University of Alaska Anchorage	mali5@uaa.alaska.edu

Name	Company	Email
Ean Amon	Oregon State University – Northwest National Marine Renewable Energy Center (NNMREC)	amon@eecs.oregonstate.edu
Ed Lovelace	Free Flow Power	elovelace@free-flow-power.com
Eric Nelson	NREL	eric.nelson@nrel.gov
Erick Johnson	SNL	ejohns1@sandia.gov
Fotis Sotiropoulos	University of Minnesota	fotis@umn.edu
James Eder	OPT	JEder@oceanpowertech.com
Jarett Goldsmith	GL Garrad Hassan	Jarett.Goldsmith@gl-garradhassan.com
Jerry Johnson	University of Alaska	jbjohnson5@alaska.edu
Jim Thomson	University of Washington	jthomson@apl.washington.edu
Joe Prudell	Columbia Power Technologies	jprudell@columbiapwr.com
Jonathan Colby	Verdant Power	jcolby@verdantpower.com
Jonathan White	SNL	jonwhit@sandia.gov
Kelley Ruehl	SNL	kmruehl@sandia.gov
Ken Rhinefrank	Columbia Power Technologies	krhinefrank@columbiapwr.com
Marshall Richmond	PNNL	marshall.richmond@pnnl.gov
Martin Wosnik	University of New Hampshire	martin.wosnik@unh.edu
Michael Lawson	NREL	michael.lawson@nrel.gov
Mitsuhiro Kawase	NNMREC	kawase@ocean.washington.edu
Mirko Previsic	Re Vision	mirko@re-vision.net
Monty Worthington	Ocean Renewable Power Company	MWorthington@orpc.co
Neil Rondorf	SAIC	NEIL.E.RONDORF@saic.com
Pukha Lenee Bluhm	Columbia Power	pukha.lenee.bluhm@gmail.com
Vince Neary	Oak Ridge National Laboratory	nearyvs@ornl.gov
Walt Musial	NREL	walter.musial@nrel.gov
Yi-Hsiang Yu	NREL	yi-hsiang.yu@nrel.gov
Zhaoqing Yang	PNNL	zhaoqing.yang@pnnl.gov
Ryan Sun Chee Fore	DOE	ryan.suncheefore@ee.doe.gov
	Note Takers	
Name	**Company**	**Email**
Chris McCombs	NREL	Christopher.McComb@nrel.gov
Adam Nelessen	NREL	Adam.Nelessen@nrel.gov
Dan Houck	NREL	Daniel.Houck@nrel.gov
Richard Meier	NREL	Richard.Meier@nrel.gov

Appendix B: Workshop Agenda

<table>
<tr><th></th><th colspan="2">Day 1, July 9, 2012</th></tr>
<tr><td>8:00</td><td colspan="2">Registration, Continental Breakfast, and Networking</td></tr>
<tr><td>8:30</td><td colspan="2">Introductions and Welcome</td></tr>
<tr><td>8:40</td><td colspan="2">Plenary Discussion on Modeling and Testing

Chair: Brooke White, U.S. Department of Energy

Ryan Sun Chee Fore, U.S. Department of Energy
"DOE Water Power Program: Modeling, Instrumentation, and Testing"

Neil Rondorf, SAIC, TC 114 Chairman
"The Role of Standards in MHK Modeling and Testing"

Dr. Robert Thresher, National Renewable Energy Laboratory
"The Role of Measurements and Instrumentation in Modeling and Testing"

Walt Musial, National Renewable Energy Laboratory
"Wind Experience in the Design Process"</td></tr>
<tr><td>10:00 – 10:20</td><td colspan="2">20-Minute Break</td></tr>
<tr><td>10:20 – 11:20</td><td colspan="2">Plenary - Verification and Validation of MHK Modeling Tools
Chair: Jarett Goldsmith, GL - Garrad Hassan
Jarett Goldsmith, GL - Garrad Hassan
"Experience with Validating MHK Tools"

Pukha Lenee Bluhm, Columbia Power Technologies
"Validation of WEC Modeling Tools"

Jonathan Colby, Verdant Power (withdrawn due to travel problems)
"Data Needs for Validation of Tidal Design Tools and Systems"</td></tr>
<tr><td>11:20 – 12:00</td><td colspan="2">Plenary Discussion and Breakout Logistics
Facilitated Discussion – 30 minutes
1. Does the industry have the correct level of data collection, modeling, and standards activities in play to achieve commercial readiness? What's missing?
2. What can be done to accelerate commercial readiness in each of these areas?
a. Borrowing experience from other industries
b. High visibility, focused demonstration projects for wave and tidal
c. Basic or applied research experiments

Logistics for Afternoon Meetings – 10 minutes</td></tr>
<tr><td>12:00 – 1:00</td><td colspan="2">LUNCH</td></tr>
<tr><td>1:00 – 2:00</td><td>Testing Track</td><td>Modeling Track</td></tr>
</table>

	Wave Measurements **Chair: Joe Prudell, Columbia Power Technologies** **Gene Terray, Woods Hole Oceanographic Institute (Withdrew)** *"Wave Inflow Using Remote Sensing"* **Joe Prudell, Columbia Power Technologies** *"Characterizing and Optimizing System Operation at Sea"* **Al Schacher, Columbia Power Technologies** *"WEC Instrumentation and Design Experiences – From Lab to the Sea"*	**Numerical Modeling of WEC Technologies** **Chair: Ken Rhinefrank, Columbia Power Technologies** **Ken Rhinefrank, Columbia Power Technologies** *"The Role of Computer Modeling in WEC Technology Development"* **Alain Clement, Ecole Centrale de Nantes** *"Numerical Modeling of WECS at Ecole Centrale de Nantes"* **Kelley Ruehl, Sandia National Laboratories** *"WEC Model Development at Sandia"*
2:00 – 2:30	**Part 1: Wave Testing Group Discussions** • Are the existing wave instruments sufficient for design and model validation? • What additional measurement capabilities would be desirable and for what purpose? (e.g., tuning) • Can we accurately extrapolate to determine extreme external event conditions and loads?	**Part 1: WEC Modeling Group Discussion** • Do we need dedicated models for each type of WEC? • What fidelity is needed to advance to commercial readiness? • What are the key outputs needed: energy performance, load response, stress/strain, and so on?
2:30 – 2:50	**20-Minute Break**	
2:50 – 4:30	**Water Current:Resource and Performance Measurements** **Chair: Monty Worthington, Ocean Renewable Power Company** **Monty Worthington, Ocean Renewable Power Company** *"Resource and Inflow Monitoring at ORPC"* **Jim Thomson, APL, University of Washington** *"Tidal Flow Turbulence Measurements"* **Vince Neary, Oak Ridge National Laboratories** *"Turbulence Measurement Methods"*	**Numerical Modeling of WEC Technologies** **Chair: David Kring, Navatek** **David Kring, Navatek** *"Coupled Dynamics Simulation in a Wave Environment"* **Diana Bull, Sandia National Laboratories** *"MHK Reference Model: Relevance to Computer Simulation"* **Yi-Hsiang Yu, National Renewable Energy Laboratory** *"NREL's WEC Modeling Tools"*

	Ed Lovelace, Freeflow Power *"River Hydrokinetic Measurement and Characterization of the Equipment Performance and Water Resource"* **Brett Prairie, Rockland Scientific** *"Challenges and Instrumentation Solutions to Understanding the Nature of Tidal Flows"*	**Kelley Ruehl, Sandia National Laboratories** *"Regional Wave Field Modeling and Array Effects"* **Jarett Goldsmith, GL Garrad Hassan** *"WaveDyn: A Design Tool for Performance & Operational Loads Modeling of WECs"*
4:30 – 5:00	**Part 2: Current Testing Group Discussions** • Are the current instruments sufficient for design and model validation? • What additional measurement capabilities would be desirable and for what purpose? (e.g., tuning) • Can we accurately extrapolate to determine extreme external event conditions and loads? • What turbulence data and how much data are needed to understand its effect on the device design?	**Part 2: WEC Modeling Group Discussion** • Do we need dedicated models for each type of WEC? • What fidelity is needed to advance to commercial readiness? • What are the key outputs needed: energy performance, load response, stress/strain, and so on?
5:00	End of Day 1	

	Day 2, July 10, 2012	
8:00	Continental Breakfast and Networking	
8:30	Welcome Back, Logistics	
8:40 – 10:00	**Testing Track**	**Modeling Track**
	Structural Load Measurements **Chair: Jim Eder, Ocean Power Technologies** **Martin Wosnik, University of New Hampshire** *"Instrumentation for Current Turbine Testing"* **Alan Turner, Micron Optics** *"Fiber Optic Sensors in a Marine Environment Past, Present, and Future"*	**Numerical Modeling of Current Technologies** **Chair: Jonathan Colby, Verdant** **Jonathan Colby, Verdant** *"Verdant Current Modeling Methods and Validation"* **Zhaoqing Yang, Pacific Northwest National Laboratories** *"Modeling the Limits and Effects of Energy Extraction from Tidal Streams and River Reaches"*

	Jon White, Sandia National Laboratories *"Experience with Fiber Optic Sensors on Wind Turbines"* **Jerry Johnson, University of Alaska, Fairbanks** *"Debris Detection Measurement Methods"*	**Erick Johnson, Sandia National Laboratories** *"Performance and Environmental Effects of MHK Devices: SNL-EFDC and CACTUS"* **Marshall Richmond, Pacific Northwest National Laboratories** *"Field Characterization of Turbulent Inflow and Collision Modeling for MHK Turbines"*
10:00 – 10:30	**Structural Loads Group Discussions** • Are the existing instruments sufficient for design, model validation, and certification? • What load and dynamic response measurements should be required to certify a device in accordance with anticipated IEC standards? • How should an instrumentation system for making MHK measurements be validated? • Are the current instruments capable of withstanding extreme events?	**Part 1: Current Modeling Group Discussions** • What turbulence data and how much data are needed to understand its effect on the device design? • Do we need dedicated models for each type of current device? • What fidelity is needed to advance to commercial readiness? • What are the key outputs needed: energy performance, load response, stress/strain, and so on?
10:30 – 10:50	**20-Minute Break**	
10:50 – 11:50	**Laboratory Measurements** **Chair: Arnie Fontaine, Applied Research Laboratory, Pennsylvania State University** **Arnie Fontaine, Applied Research Laboratory, Pennsylvania State** *"Overview of the State-of-the-Art Laboratory Instrumentation Systems"* **Ean Amon, Oregon State University** *"Instrumentation for WEC Testing"* **Muhammad Ali, University of Alaska, Anchorage** *"Instrumentation of Current Technology Testing and Replicating Harsh Environments"*	**Numerical Modeling of Current Technologies** **Chair: Al LiVecchi, National Renewable Energy Laboratory** **Mike Lawson, National Renewable Energy Laboratory** *"Hydro-FAST Axial Flow Simulation Code Development"* **Alison Cribbs, Ecomerrit** *"Modeling Options for Current Energy Convertor Systems and Associated Challenges"* **Danny Sale, University of Washington** *"Harp-OPT Optimization Code for Axial Flow System Design"*

11:50 – 12:20	**Laboratory Testing Group Discussions** • What role does laboratory testing currently play in the design process? • What data can be obtained in the laboratory that cannot be obtained by open-ocean testing? • Are the current facilities sufficient to achieve commercial readiness? • Are there any facility gaps that would reduce development cost?	**Part 2: Current Modeling Group Discussions** • What turbulence data and how much data are needed to understand its effect on the device design? • Do we need dedicated models for each type of current device? • What fidelity is needed to advance to commercial readiness? • What are the key outputs needed: energy performance, load response, stress/strain, and so on?
12:20	**Lunch**	
1:20 – 2:40	**Sensors and Instrumentation** **Chair: Mirko Previsic, Re Vision Consulting, LLC** **Mirko Previsic, Re Vision Consulting, LLC** *"Wave Tank Testing and Model Validation – An Integrated Approach"* **Eric Nelson, National Renewable Energy Laboratory** *"MOISyT Instrumentation System and Recent Field Experience"* **Jim Eder, Ocean Power Technologies** *"An Empirical Demonstration of Deterministic Sea Wave Prediction on Power Output"* **Borna Hamedni, Ocean Power Technologies** *"Sea Wave Prediction Using Upstream Sensors"*	**Modeling of MHK Turbines** **Chair: Ryan Sun Chee Fore, U.S. Department Of Energy** **Fotis Sotiropoulos, University of Minnesota** *"Numerical Simulation of MHK Devices in Real-Life Waterways: Recent Advances and Future Challenges"* **Mitsuhiro Kawase, National Northwest Marine Renewable Energy Center** *"Effects of Localized Energy Extraction in an Idealized, Energetically Complete Numerical Model of an Ocean-Estuary Tidal System"* 2:00 – 3:10 **Modeling Needs Forum** **Chair: Ryan Sun Chee Fore, U.S. Department Of Energy** A guided discussion with DOE on modeling needs, current efforts, and strategies moving forward.
2:40 – 3:10	**Sensors and Instrumentation Discussion** • Are the existing wave instruments sufficient for design and model validation? • What additional sensors and instruments would be desirable and why?	

	• How can these measurements be used to improve reliability and reduce O&M? • Do we have the capability to measure with enough accuracy extreme events and loads?	
3:10 – 3:40	**30-Minute Break**	
3:40 – 4:10	**Open Discussion of Industry Needs**	
4:10 – 4:40	**Continuation of Workshop Findings and Closeout**	
4:40	End of Workshop and Announcements	

	Day 3, July 11, 2012
9:00 – 12:00	Tour of National Wind Technology Center (Approximately 20 people participated in the tour)

Appendix C: Workshop Presentations

Presenters and titles of presentations given at the workshop are given below. Abstracts were requested from all speakers and are included (unabridged) if they were provided by the presenter.

Plenary Session

Ryan Sun Chee Fore, U.S. Department of Energy
"*DOE Water Power Program: Modeling, Instrumentation, and Testing"*

A key objective of the U.S. Department of Energy's (DOE's) Marine and Hydrokinetic (MHK) Technology Development portfolio is to develop tools for design optimization, enable measurements to maximize learning from our deployments, and provide opportunities/venues for testing. For tidal and current devices, we can leverage the turbulence, blade optimization, and overall rotor performance models that have been developed through the wind industry. Wave energy devices present a new physics challenge for our community that has the potential to leverage other communities with expertise in floating systems and dynamics. DOE is working through our national laboratories to develop and release these open-source tools for MHK device developers.

It is important to gain operational experience by "getting steel in the water," but it is equally important to build an understanding of the fundamental behavior of the devices being demonstrated. That is why DOE believes that it is critical to collect and share data that gives us insight into why things happened, rather than simply establishing what happened. Only in this way can we hope to progress from prototype demonstrations to production-level deployments. DOE's role is to facilitate the collection and sharing of data necessary to further our understanding of the underlying phenomenon and validate the tools used to predict that phenomenon.

Testing infrastructure is critical to technical maturation of our industry and essential to building and maintaining our domestic strength. We need a domestic capability to assess the performance of devices developed in the United States. This year, our national labs completed a testing needs assessment identifying two critical gaps: a large-scale (TRL 5/6) controlled wave tank and grid-connected open water test berths for TRL 7/8 demonstrations.

Neil Rondorf, SAIC, TC 114 Chairman
"The Role of Standards in MHK Modeling and Testing"

Below is a status of the International Electrotechnical Commission (IEC) Technical Committee (TC) -114. The TC is developing the international industry standards for marine and hydro-kinetic devices to harvest energy from wave, tidal, and in-current stream technology concepts. There are 14 countries around the world that are actively engaged in the standards development and are contributing significantly to the effort. There are presently 10 project teams functioning as technical writers for each of the separate standards being generated. Canada, the Republic of South Korea, the United States, the United Kingdom, Denmark, and Ireland are all playing leading roles in this effort.

The importance of these standards to the MHK industry centers on the ability to provide credibility and support device and project development. There are numerous examples of why it is essential to apply these standards to developing devices and projects. These standards can be used to reduce risk, lower insurance costs, and enhance market confidence and financing. The process and background in the standards development is important to assist interested parties in understanding the roles they can play as individuals or companies in actively participating in the U.S. effort.

The U.S. Technical Advisory Group is organized around the project team structure so a U.S. "shadow committee" reflects or mirrors the international project team. The shadow committee chairs and members include academia, industry, nongovernment organizations, and government personnel supporting MHK programs.

Dr. Robert Thresher, National Renewable Energy Laboratory
"The Role of Measurements and Instrumentation in Modeling and Testing"

This presentation uses two historical examples from the development of wind energy to illustrate the interaction and synergy between experiments and modeling, as well as how the development of consensus international standards is facilitated by collaboration. The first example is about how turbulence wind inputs were shown to be a significant contributor to the dynamic loads experienced by wind turbines. During the development of wind systems, it was discovered through experimental measurements on prototype turbines that the measured blade cyclic loading was much higher than the model-predicted design loading. Later, through subscale wind tunnel testing, it was shown that, even for steady flow conditions in the tunnel, small wiggles in the tunnel velocity profile caused relatively large rotor cyclic loading, leading to the conclusion that wind turbulence could be the cause of the higher-than-predicted cyclic rotor loading. Subsequent focused research in the United States and Europe showed that turbulence excitation caused the design driving loads for rotor fatigue and ultimate strength. Because of the collaborative international research on this topic, consensus on the importance of turbulence loads cases in the design standard for wind turbines, IEC 61400-1, was almost a foregone conclusion.

The second historical example was the unsteady aerodynamics experiment, which again used wind tunnel experimental measurements to show that dynamic stall modeling was not correctly predicting wind turbine dynamic loads in the stalled flow regime. In this case, a 10-m diameter turbine was tested in the NASA Ames 80- by 120-ft test section and operated under stalled flow conditions. Subsequently, through a collaborative international blind code comparison, it was clearly demonstrated that the codes could not predict dynamic stall hysteresis adequately and that further research would be needed. In this case again, experimental measurements compared with modeling results through international collaboration resulted in the general consensus that the then-current stall models needed improvement to give reliable predictions for wind turbine dynamic loads, and this needed to be recognized in the design standard. In conclusion, the presentation illustrates the importance of synergistic modeling and experimental measurements together with international collaboration in developing realistic and trustworthy consensus international design standards.

Walt Musial, National Renewable Energy Laboratory
"Wind Experience in the Design Process"

There are numerous lessons that can be learned from the experiences of the wind energy industry over the past 3 decades that can be transferred to the MHK industry of today. Wind energy experienced tremendous growth during the early 1980's, when over 10,000 wind turbines were installed in California, largely due to very aggressive policy incentives. During this period of nascent growth, the industry learned many of the key lessons that have determined the basic architecture of modern turbines. Ultimately, the design process was developed and refined around iterative testing and modeling loops that served to mature wind turbines at a faster rate and helped define the process for applying modern standards that help assure commercial viability. MHK systems have not yet gone through the same level of deployment. Because of constraints on regulations and siting, the MHK industry will not likely have the same opportunity to deploy as many systems with the same degree of trial and error as wind. Therefore, MHK systems must be deployed smarter and with a higher degree of predeployment preparation and test readiness to make the most of every system that is deployed. MHK systems can make use of the mature design process of wind energy to help avoid mistakes and accelerate TRL advancement.

Jarett Goldsmith, GL Garrad Hassan
"Experience with Validating MHK Tools"

GL Garrad Hassan (GL GH) is an industry-leading, independent renewable energy consultancy with involvement in many wave and tidal energy projects around the world. To support this work in marine renewables, GL GH has developed a suite of modeling tools specifically for use in the wave and tidal energy sectors. This includes the device design tools Tidal Bladed and WaveDyn, and the array design tools TidalFarmer and WaveFarmer. Validation of the tools using real data has been central to the development process and ensures the creation of reliable design tools. The presentation discusses various validation exercises that have occurred for the different wave and tidal design tools. This includes comparison of models to data from testing undertaken by several device developers, and the work resulting from two large projects (greater than $10 million) funded by the Energy Technologies Institute in the United Kingdom, one of which is led by GL GH.

Pukha Lenee Bluhm, Columbia Power Technologies
"Validation of WEC Modeling Tools"

Instrumentation and Testing

The following presentations were given on instrumentation and testing.

Wave Measurements

Joe Prudell, Columbia Power Technologies
"Characterizing and Optimizing System Operation at Sea"

Al Schacher, Columbia Power Technologies
"WEC Instrumentation and Design Experiences – From Lab to the Sea"

Water Current: Resource and Performance Measurements

Monty Worthington, Ocean Renewable Power Company
"Resource and Inflow Monitoring at ORPC"

Ocean Renewable Power Company (ORPC) is a leading developer of hydrokinetic technology and projects for tidal, river, and ocean current applications. ORPC has developed proprietary technology including TidGen, RivGen, and OCGen Power Systems to harness these resources. ORPC has project sites permitted by the Federal Energy Regulatory Commission in the Bay of Fundy, Maine, Cook Inlet, Alaska, and the Tanana River, Alaska, and is currently installing the first grid-connected tidal energy project in the United States at its Cobscook Bay site near Eastport, Maine.

As part of ORPC's technology and project development work, it is essential to collect rigorous data on hydrokinetic resources at project sites and real-time information on current inflow velocities. ORPC relies primarily on four techniques for these measurements: 1) roving, surface-mounted Acoustic Doppler Current Profiler (ADCP) measurements for site reconnaissance, model verification and characterization of river energy, 2) bottom-mounted stationary ADCP measurements to measure energy density and fine-scale spatial surveys at tidal sites, model verification, and characterization of seasonal variation in river current velocities, 3) fixed-mount ADCP on ORPC turbine generator units (TGUs) for measurement of inflow to TGUs, and 4) electromagnetic current meter for velocity measurement at the TGUs.

Jim Thomson, APL, University of Washington
"Tidal Flow Turbulence Measurements"

Field measurements of turbulence are presented from two sites in Puget Sound, Washington, that are proposed for tidal energy development. Time series data from multiple acoustic Doppler instruments are analyzed to obtain statistical measures of fluctuations in both the magnitude and direction of the tidal currents. The resulting turbulence intensities are typically 10% at the hub heights of the proposed turbines. Length and time scales of the turbulence are also analyzed. Large-scale, anisotropic eddies dominate the turbulent kinetic energy spectra. Data quality and sampling parameters are discussed, with an emphasis on the removal of Doppler noise from turbulence statistics. In addition, deployment strategies, including motion correction of data from compliant moorings, are discussed.

Vince Neary, Oak Ridge National Laboratories
"Turbulence Measurement Methods"

Ed Lovelace, Freeflow Power
"River Hydrokinetic Measurement and Characterization of the Equipment Performance and Water Resource"

Brett Prairie, Rockland Scientific
"Challenges and Instrumentation Solutions to Understanding the Nature of Tidal Flows"

In characterizing tidal energy resources, turbulence measurements have been identified as a key requirement for optimizing designs of tidal-current devices. Environmental turbulence and its interaction with these devices significantly affect unsteady turbine loading and performance. This presentation introduces an instrument solution for in-situ turbulence measurements based on a combination of sensor technologies that have been tested in offshore deployments. At the core of the sensor suite is the velocity shear probe, which is a standard sensor for measuring dissipation-scale turbulence in the ocean. The shear probe resolves turbulent length scales near the dissipation range. We evaluate the application of the shear probe in tidal channel flows, presenting data examples of measurements from a vertical profiler deployed in a tethered free-fall mode. The data resolve turbulent velocity fluctuations over length scales of several centimeters to the order of 1 m. The shear probe sensor has a wide dynamic range, resolving vertical changes of turbulent kinetic energy dissipation ranging from 10-10 to 10-4 W/kg. The results demonstrate the suitability of the shear probe-based measurement to understanding the nature of tidal flows over length scales associated with turbine blade dimensions, rotor dimensions, array separations, and array footprints.

To gather high-resolution, time-series data necessary to understand the nature of turbulence in cyclical tidal flows, Rockland Scientific International Inc. has been working with NREL to produce an autonomous smart mooring system with an acoustic (ADV) and non-acoustic (shear probe) sensor package capable of continuously monitoring full-spectrum turbulence near tidal energy devices.

Structural Load Measurements

The following presentations were given on structural load measurements.

Martin Wosnik, University of New Hampshire
"Instrumentation for Current Turbine Testing"

Alan Turner, Micron Optics
"Fiber Optic Sensors in a Marine Environment Past, Present, and Future"

Jon White, Sandia National Laboratories
"Experience with Fiber Optic Sensors on Wind Turbines"

Jerry Johnson, University of Alaska, Fairbanks
"Debris Detection Measurement Methods"

In 2010, three in-stream hydrokinetic demonstration projects (at Ruby and Eagle, Alaska, and at Ft. Simpson, Yukon Territories) were discontinued because of the effects of woody debris collecting on the turbine floating platforms or damage to a turbine blade. To develop methods and technology to mitigate the debris hazard, the Alaska Hydrokinetic Energy Research Center is characterizing the nature of surface and subsurface debris and developing mitigation methods and technology. A time-lapse camera system is used to monitor surface debris. Subsurface debris is observed using high-resolution sonar, a mechanical debris detection device, and direct observation. Current mean velocity and turbulence is measured using an acoustic Doppler current profiler. A research debris diversion platform is used to examine the ability to protect downstream infrastructure from surface debris and the consequent effects on river current velocity. Debris occurs throughout the water column with increasing frequency and mass as river stage increases. Debris can occur as individual pieces or as large debris islands. Subsurface debris appears to exist primarily at the riverbed, but vertical logs and neutrally buoyant logs also are observed. Debris diversion methods or placing the hydrokinetic device just outside of the main debris path channel significantly reduce debris effects, but reduce the near downstream velocity.

Laboratory Measurements

Arnie Fontaine, Applied Research Laboratory, Pennsylvania State University
"Overview of the State-of-the-Art Laboratory Instrumentation Systems"

This presentation provides an overview of the state of the art in laboratory instrumentation used in hydrodynamic testing of marine devices. In general, test goals should drive the test program instrumentation needs relative to low cost, simple, low resolution, and accuracy, up to high cost, complex, high resolution, and accuracy. Advantages and disadvantages of invasive versus noninvasive instrumentation systems are discussed. Overviews of different measurement systems are provided for: 1) structural/mechanical measurements (steady and unsteady loads and device and component motion and vibration), 2) flow and velocity (volume flow, multicomponent velocity, pressure, flow stresses, and cavitation), 3) wave height, and 4) acoustics. Examples of commonly used, well-accepted, validated systems and new, state-of-the-art, research-grade systems are provided with overviews of operating characteristics such as spatial and temporal resolution, accuracy, advantages and disadvantages, and known sources of error. References are provided for additional information.

Ean Amon, Oregon State University
"Instrumentation for WEC Testing"

Facilities and instrumentation are presented for testing wave energy converter (WEC) prototypes at the Northwest National Marine Renewable Energy Center (NNMREC) at Oregon State University (OSU). These facilities include the O.H. Hinsdale Wave Research Laboratory (HWRL) and the Wallace Energy Systems and Renewables Facility on the OSU campus, as well as sites for scaled field testing and NNMREC's open-ocean test site, located offshore in Newport, Oregon. Available instrumentation used in previous tests is discussed with examples shown from previously completed scaled testing. Lastly, an introduction is given for the Ocean Sentinel Instrumentation Buoy currently under development for testing WECs at NNMREC's open-ocean test site, with the first deployment scheduled in August 2012.

Muhammad Ali, University of Alaska, Anchorage
"Instrumentation of Current Technology Testing and Replicating Harsh Environments"

The ORPC tested their first prototype hydrokinetic device in Passamaquoddy Bay in 2008. After a year of testing, ORPC found significant wear on the device's main shaft bearings and generator seals, which negatively impacted the generator performance and functionality. To investigate bearing and seal wear rates in the sedimented salt water conditions, the University of Alaska Anchorage team designed and developed a flume. Essentially, the flume re-creates the hydrodynamic, salinity, sedimentary, and mechanical loading environment that the ORPC hydrokinetic device components faced in the field deployment. The main flume components include: a flow conduit to direct the recirculating flow efficiently, a pump to drive the flow, a rotating shaft where the bearings and seals are positioned, a motor to drive the shaft, an actuator to apply the appropriate load to the bearings and shaft, and a chiller/heat exchanger system to maintain the water temperature at the desired level. A customized instrumentation system is developed in the flume to monitor fluid flow rate, temperature, mechanical vibrations, bearing load, bearing wear rate, shaft power input, seal leakage, and turbidity in the areas of interest. The University of Alaska Anchorage team is currently testing different types of polymer, metal, and hybrid bearings and mechanical seals. This DOE-sponsored study will play a critical role in improving the life, performance, and reliability of hydrokinetic devices that are currently deployed or will be deployed in sedimented water bodies.

Sensors and Instrumentation

Mirko Previsic, Re Vision Consulting, LLC
"Wave Tank Testing and Model Validation – An Integrated Approach"

This presentation summarizes some of the key lessons learned by RE Vision in the areas of physical modeling and validation of theoretical models and presents a set of approaches and potential solutions to existing issues. The presentation demonstrates how processes could be developed that would improve the accuracy and efficiency of device modeling and validation work. The primary focus is on the reduction of time and cost required to develop validated, computationally efficient, theoretical models that can serve as engineering tools for design optimization and trade-off studies.

The presentation touches on the following issues: (1) appropriate dynamic modeling of different WEC devices, (2) a review of recent tank testing programs carried out in relatively inexpensive West Coast wave tanks, and their infrastructure issues, (3) the cost of carrying out wave tank testing, (4) sensors and instrumentation used and required for additional research and development to fill existing capability gaps, (5) the representation of the power take off system in subscale models, (6) the utilization of RE Vision's theoretical wave tank to provide instantaneous feedback on data quality issues, and (7) the utilization of computational fluid dynamics to determine viscous drag terms that can be utilized in computationally efficient dynamic codes for optimization purposes.

Eric Nelson, National Renewable Energy Laboratory
"MOISyT Instrumentation System and Recent Field Experience"

NREL designed and built the Modular Ocean Instrumentation System (MOISyT) testing platform and deployed it at multiple testing sites during 2012. As of July 2012, these deployments included the free-low power Mississippi River turbine test, University of New Hampshire General Sullivan bridge tidal turbine test, and the SWAY floating offshore wind platform test in Norway. A brief description of the MOISyT architecture, pictures of deployments, and up-to-date lessons learned from the MOISyT deployments are all presented.

Jim Eder, Ocean Power Technologies
"An Empirical Demonstration of Deterministic Sea Wave Prediction on Power Output"

Borna Hamedni, Ocean Power Technologies
"Sea Wave Prediction Using Upstream Sensors"

Modeling

The following modeling-related presentations were given.

Numerical Modeling of WEC Technologies

Ken Rhinefrank, Columbia Power Technologies
"The Role of Computer Modeling in WEC Technology Development"

Alain Clement, Ecole Centrale de Nantes
"Numerical Modeling of WECs at Ecole Centrale de Nantes"

Kelley Ruehl, Sandia National Laboratories
"WEC Model Development at Sandia"

The Sandia National Laboratories (SNL) presentation on "Wave Energy Converter Model Development at Sandia" is a review of SNL's ongoing WEC modeling activities, with an introduction to SNL's Wave Energy Development Roadmap. The roadmap was created to relate Technology Readiness Levels (TRLs) to corresponding modeling and experimentation efforts. The roadmap provides a suggested path from design to commercialization, intended to clarify needs for different modeling and experimental fidelity, as well as to identify research gaps to promote industry success. Finally, the focus shifts to SNL's current WEC research projects, providing an introduction to SNL's reference models and current modeling capabilities.

David Kring, Navatek
"Coupled Dynamics Simulation in a Wave Environment"

Navatek, Ltd. is a research shipyard based in Honolulu, Hawaii, that is primarily involved with the development of computational tools and new naval prototypes for the U.S. Navy. Navatek is also involved in alternative-energy wind and waves projects and worked with Ocean Power Technologies, Inc., in 2005 to fabricate and deploy a WEC.

Navatek's experience in naval research may provide some interesting technologies for the MHK community. One particular item is the computational hydrodynamics code AEGIR (named for the Norse god of the sea). AEGIR is a recent descendent of the radiation-diffraction code WAMIT, a staple in the offshore and MHK communities. While WAMIT is a linear, frequency-domain code for offshore platforms in no water current, AEGIR is a nonlinear, time-domain code for ships and platforms either moving with forward speed or operating in a current. AEGIR applies NURBS-based CAD geometric representations that are based on industry standards. Beyond AEGIR, there are some associated Navatek tools such as NavADE, which supports hydrodynamic optimization that could be of interest to WEC development.

Navatek could collaborate with the MHK community on construction, hydrodynamic analysis, and optimal design.

Diana Bull, Sandia National Laboratories
"MHK Reference Model: Relevance to Computer Simulation"

This presentation outlines how the reference model project utilizes computer simulation. An overview of the WEC design process is provided to outline the presentation and the reference model project. This process highlights the distinct component models that are necessary to feed into a final design. A subset of these component models are then explored in the presentation. The presentation highlights how the reference model project approaches climate modeling, performance modeling, anchor and mooring modeling, structural modeling, and power take off modeling. Simulation results and analysis are presented for each of the component models for a particular reference model.

Yi-Hsiang Yu, National Renewable Energy Laboratory
"NREL's WEC Modeling Tools"

This presentation addresses the recent wave energy converter modeling efforts from NREL. The studies include the computational fluid dynamics simulations and experimental wave tank tests of a two-body floating-point absorber. The work also involves the development of a frequency domain analytical solution tool for evaluating the response dynamics and power performance of point absorbers and the validation of numerical tools. In addition, a framework for future modeling tool development was presented. The work includes the current research projects and tool development efforts as well as NREL's vision of the need for modeling tools for WEC systems and development strategies.

Kelley Ruehl, Sandia National Laboratories
"Regional Wave Field Modeling and Array Effects"

The SNL presentation on "Regional Wave Field Modeling and Array Effects" is a review of the laboratory's current WEC modeling research efforts, including SNL's current modeling capabilities and model tool development activities. Emphasis is placed on the WEC Farm modeling tool development activities. These activities include SNL's WEC Farm sensitivity analysis performed in Monterey Bay, California, which uses Simulating WAves Nearshore's (SWAN's) standard WEC modeling capabilities. In its existing form, SWAN models WECs as frequency-independent transmission and reflection coefficients. Results of the Monterey Bay sensitivity analysis were used to inform another sensitivity analysis performed at the Oregon State University (OSU) Hinsdale Tsunami Basin. SNL's future efforts include modifying the SWAN source code to better model WECs, and to use the WEC Farm experimental data collected at OSU to validate the modified version of SWAN.

Jarett Goldsmith, GL Garrad Hassan
"WaveDyn: A Design Tool for Performance & Operational Loads Modeling of WECs"

GL Garrad Hassan (GL GH) is an industry-leading independent renewable energy consultancy with involvement in many wave and tidal energy projects around the world. In past years, the young wave energy sector lacked a software tool that considers the unique modeling requirements for WECs, is validated for these applications, can provide detailed information to inform design, and is flexible enough for use on a range of WEC concepts. This need led GL GH to develop a specific device design tool to allow performance and operational loads modeling of WECs. This tool, named WaveDyn, allows WEC simulations to be run in the time domain while accounting for the influence of all the main subsystems, including hydrodynamics, power take off and control, structural dynamics, and moorings in a fully coupled model. A flexible, multibody approach enables the modeling of a variety of very different WEC concepts seen in the sector today. Time-domain simulations enable the modeling of real sea input conditions and important nonlinear effects. The philosophy and approach behind WaveDyn's development and some of its applications are presented.

Numerical Modeling of Current Technologies

Jonathan Colby, Verdant
"Verdant Current Modeling Methods and Validation"

Under a contract from the DOE Advanced Water Power Program, "Improved Structure and Fabrication of Large, High-Power KHPS Rotors," Verdant Power has advanced the state-of-the-art computational modeling of the fluid dynamics associated with marine kinetic hydropower systems. Working in collaboration with the University of Minnesota, the University of California Davis, Oak Ridge National Laboratory, SNL, and NREL, progress has been made in numerical modeling and the collection of design validation data for the Gen5 tidal turbine. Using both large eddy simulation and Reynolds Averaged Navier-Stokes models, detailed analysis of rotor performance, three-dimensional wake characteristics, and expected turbine loading at larger scales have been conducted. Model validation was accomplished with full-scale (5 m) in situ measurements of turbine performance and tidal flow characteristics. Acoustic Doppler Velocimeter (ADV) measurements were also collected at the turbine hub height, with a focus on turbulence phenomena inherent in tidal currents. These efforts represent an advancement in the understanding of fluid-structure interactions, the influence of turbulence on turbine performance and loading, and the evolution of the rotor wake downstream; all with a focus on the reliability and longevity of larger commercial tidal machine design.

Zhaoqing Yang, Pacific Northwest National Laboratory
"Modeling the Limits and Effects of Energy Extraction from Tidal Streams and River Reaches"

Erick Johnson, Sandia National Laboratories
"Performance and Environmental Effects of MHK Devices: SNL-EFDC and CACTUS"

Marshall Richmond, Pacific Northwest National Laboratory
"Field Characterization of Turbulent Inflow and Collision Modeling for MHK Turbines"

Mike Lawson, NREL
"Hydro-FAST Axial Flow Simulation Code Development"

Over the past several decades, numerical modeling tools have helped the wind turbine industry achieve commercial viability by enabling the rapid development, analysis, and certification of turbine designs. The recent emergence of the hydrokinetic turbine industry in the United States and across the globe has created the need for a similar set of hydrokinetic turbine design and analysis tools. Accordingly, NREL is developing a suite of open-source, public-domain numerical modeling tools that meet the needs of the hydrokinetic turbine industry. To develop these tools quickly, NREL's wind turbine design and analysis codes are being adapted to model hydrokinetic axial-flow (i.e., horizontal-axis) turbines. The following list describes the codes NREL is developing as part of this effort:

- HydroFAST: A time-domain wind turbine simulation tool for land and offshore turbines. It is comprised of a suite of code modules that simulate the aerodynamic, hydrodynamic, and structural components of wind turbines (e.g., a tower, nacelle, rotor, and so on).
- HydroTurbSim: A simulator of turbulent flows in the oceans, tidal streams, and rivers. TurbSim output provides realistic atmospheric inflow conditions to HydroFAST so that modeled loads and performance characteristics are representative of those turbines experienced in realistic oceanic conditions.
- HARP-Opt: A rotor design code that utilizes blade element momentum theory and a genetic optimization algorithm to determine the blade shape and rotor operating characteristics that maximize annual energy production for a user-specified flow distribution.

Alison Cribbs, Ecomerrit
"Modeling Options for Current Energy Converter Systems and Associated Challenges"

MHK energy technologies have significant potential to contribute to the future supply of cost-effective renewable energy. DOE has estimated that more than 5,000 gigawatts (GW) of energy are available from the world's ocean currents. To cost-competitively harness this energy, robust systems requiring minimal maintenance are required.

A successful system design can only be reached with a thorough understanding of the flow field, which, when modeled accurately, will help to reduce conservative factors of safety for all aspects of the design. This has a particular effect with regards to blade and bearing design. Because models with loads derived from resource data are only as good as their inputs, it is necessary to devise unique solutions that combine point measurements and acoustic Doppler current profilers to provide shear data and resolution within platform/rotor response times. This accuracy is nonexistant with traditional instrumentation.

With an enhanced understanding of the boundary conditions, models ultimately support the optimization of power-to-weight ratios and achievement of cost-of-energy targets. This presentation briefly outlines the modeling process and discusses challenges and opportunities for improving existing techniques for ocean current energy conversion.

Danny Sale, University of Washington
"Harp-OPT Optimization Code for Axial Flow System Design"

Modeling of MHK Turbines

Fotis Sotiropoulos, University of Minnesota
"Numerical Simulation of MHK Devices in Real-Life Waterways: Recent Advances and Future Challenges"

Mitsuhiro Kawase, National Northwest Marine Renewable Energy Center
"Effects of Localized Energy Extraction in an Idealized, Energetically Complete Numerical Model of an Ocean-Estuary Tidal System"

Ocean tide is forced by astronomical processes at the global scale; however, most regional models of marine hydrodynamics have tides forced with boundary conditions instead. This introduces uncertainties into results from regional model study in tidal energy applications. We have constructed a highly idealized model of the ocean-estuary system, in which tides are forced astronomically, thus the integrated energy balance has no exchange with the "outside" ocean. We perform benchmark energy extraction experiments to establish scaling between energy dissipation by a tidal array and changes in the tidal parameters. We then repeat the experiments with a series of subdomain models, for which tides sampled from the full domain model are used as boundary conditions. Both the full domain and the subdomain models yield a scaling relationship between energy extraction and tidal range in agreement with earlier theoretical studies; however, estimates of the maximum physically extractable energy are sensitive to the regional model configuration due to the extraction, thereby causing changes in energy flux at the domain boundary and lack of direct tidal forcing within the subdomain model. Adding the latter into the subdomain model leads to a small but significant improvement in the agreement of results with the full domain model.

Appendix D: Notes from Facilitated Discussion Sessions

Day 1: Plenary Session Discussion

The following questions and issues were addressed during the first plenary session.

- How do we develop confidence in modeling and simulations tools?
    - Need consistency to facilitate investor confidence
    - The U.S. Navy has dealt with this issue—leverage their experience
    - Create a cost-effective testing program to provide the necessary validation data
    - Develop modeling tools to capture key elements (e.g., structural load), but not all elements (e.g., detailed hydrodynamics).
- What is the role of measurements and instrumentation in modeling and testing?
    - "All models are wrong…some are useful" quote from Robert Thresher—we need high-quality test data to know what models are useful
    - Through failure comes learning. Make sure you understand how and why things failed.
- Was the development of knowledge of atmospheric/meteorological sciences important to developing wind power?
    - Yes, very. Atmospheric stability and how turbulence is propagated influences wind turbine loads and must be understood.
- The Unsteady Aerodynamics Experiment was a large-scale wind turbine test performed in the NASA Ames 80- by 120-ft wind tunnel. The test produced a high-quality data set that is still being used today by the wind energy community for a variety of purposes, including numerical and experimental validation; possibly the best data set available today.
    - How long did the Unsteady Aerodynamics Experiment (UAE) at NASA take and what was the cost?
        - Several million dollars spent from 1988 to 2000
        - The actual tunnel test took 2 weeks. Preparation was 18 months for just that phase.
    - There is currently no grand experiment like this in process in the MHK industry.
- In wind, there were things we didn't know we didn't know (e.g., turbulence importance). What are the known unknowns?
    - The wave energy industry has lots of similar unknown problems
    - Turbulence in the array: currently studying this topic with high-performance computing

- The tendency to keep information internal for the sake of a market advantage takes away from the opportunity for the entire industry to move forward.
- What do you view as the most critical environmental information that affects the device? What data needs to be collected?
    - Measurement programs that predict long-term wave elevation data are needed
    - Frequency contents of 100- to 150-year storm events is required to design for extreme events. How can we estimate this?
- For survival conditions, cresting, slapping, and breaking waves must be considered.
    - Modeling these phenomena are very difficult
    - Consider a brute-force approach to do phase-resolving (full modeling, made more feasible recently, DNS, and so on). This approach is computationally intensive, but allows for significant data collection.
    - This may be something that is answered by experimentation and experience in testing.
        - Need a standard on how to extrapolate data to 100-year wave events
        - Borrow methodology from flood engineering
        - Borrow information from the oil and gas industry. However, it is necessary to recognize the fact that this industry has more funding and more opportunity for loss of life and therefore higher safety factors.
    - How do we consider the transition from instrumentation for testing to instrumentation for operating devices?
        - Need a measurement validation program to avoid heavy instrumentation on operating devices
        - Need instruments for failure load analysis and to help design longer-lasting devices.
    - Linear modeling tools are not adequate because many devices operate in nonlinear regimes
    - What are the numerical modeling verification and validation considerations?
    - Ensure that numerical models are simulating the same problem
    - Need agreed-upon definitions for verification and validation
    - With numerical modeling, we learn about things we know we need to learn, and with experimentation, we learn about things that we don't know we need to know.
    - Where do you see modeling going in the future? Could it predict lifecycle costs? Design and size power take off? How far can we take modeling for these devices? Can we ultimately predict the cost of energy?
        - The end goal is always to decrease the cost of energy. All models should strive to get there eventually.

        - Modeling is divided into two types: operational and survival. Survival is more difficult to model and operational provides the profit side/cost of energy.
        - Modeling improvements are needed for survival modeling.
        - Need to improve environmental impacts modeling (e.g., sediment transport)
        - GL WaveDyn models wear, maintenance, fatigue loading, and so on.
- What can we do to accelerate commercial readiness?
    - Address what materials we should use to increase design life and lower maintenance costs/cycles
    - Continually re-examine how we are allocating resources to solve all the issues with WEC and tidal devices.
- How did the wind industry create a successful commercial industry?
    - Bob Thresher: "Get stuff in the water. What was done in the wind industry was putting turbines up and breaking them. What wasn't done was proper instrumentation. All the preguessing/modeling is often a waste of time. It can be helpful in covering the obvious stuff, but the only way to expand our horizons quickly is to implement real devices. Early deployment was where the real learning took place. Invest a lot in instrumentation and get those devices out in the water."
    - Government can support instrumentation, as long as the information is open source
    - Policy to help get devices in the water will help.
- How and where should resources be allocated?
    - Better instrumentation is needed.
        - Will help gather data for model verification, extreme conditions, wave/current resource characterization, lifecycle device monitoring, and failure/survivability analysis on deployed systems.
    - Resources should also be allocated for the verification and validation of numerical models
    - Need to develop models that can predict survivability loads.

Testing Track

Day 1: Wave Testing Group Discussions

The following questions and issues were covered in the wave testing group discussions.

- What is the best control approach?
    - Is it feedback or feedforward?
    - Feedback sends torque command that is duty ratio for switches

    - If you can predict waves early enough, you use feedforward controls
    - In an array, information from upstream devices could provide feedback for downstream devices.
- Wave measurement experiences
    - All data collection is wrong too, but some is useful
    - Don't be afraid to make it if you can't find it
    - Never trust a specification sheet, do bench tests
    - Don't use connectors underwater unless you need them
    - Include instruments for environmental effects.
- What are the needs and gaps for instrumentation? Too few sensors are water- and salt-proof.
- How confident are we that we could match up measured loads from strain gauges and load cells to external conditions that caused them?
    - Not very, data are not time synchronized
    - This is a possible gap in data collection. A sensor is needed for instantaneous wave measurement; Light Detection and Ranging (LIDAR) might work. These systems could be time synchronized with load measurements.
    - Measuring directionality is the main problem
    - If a person on a boat can judge directionality and magnitude, we should be able to make a sensor that can do the same
    - IEC requires input and output to be measured simultaneously for certification.
- Are the existing wave instruments sufficient for design and model validation?
    - Need real-time measurements of directional wave
    - Need Global Positioning System and time-synchronized data
    - Need site-specific history of waves because existing data buoys are not well-located for where the devices may go.

Day 1: Current Testing Group Discussions

The following questions and issues were addressed during the current testing group discussions.

- Turbulence measurements methods:
    - Need cost-effective ways to get ADVs in the water at adjustable positions in the water column
- Could design site-specific turbines (or at least rotors) if accurate data can be gathered
- Cannot develop a costing model similar to the wind industry until we get devices in the water

- Because turbulence is a huge issue in the wind industry, we think it will likely be the same in the water industry, and as demonstrated by the blade failures of several prototype devices
- What defines a good site?
    - Average speed (i.e., energy) at the site and turbulence values
    - How do you extrapolate from limited data to extreme events and the lifetime of the device?

Day 2: Structural Loads Group Discussions

The following questions and issues were covered in the structural loads group discussions.

- Are existing instruments sufficient?
    - Some are good for prototypes, but we'll use fewer for full-scale deployments
    - Better deployment methodologies and usage standards need to be developed
- As we begin to deploy these instruments, there are measurements that will be taken that can validate at the full scale
- Fiber optic devices for strain could be used, but primarily with prototype deployments.
- MHK sensors should be certified in a similar way to wind energy sensors (e.g., cup anemometers)
- MHK device designs are very different and the lack of consistency in designs introduces different types of required measurements
- Synchronizing wave measurement with load measurement in the field is difficult because researchers can't measure instantaneous waves coming into the device
    - For an oscillating WEC device, we'd be interested in what's going on in the whole water column (velocity and directionality)
    - Promising research in wave radars for full-field representation, but calibration is very difficult in this type of sensor
- What measurements should be required for anticipated standards?
    - Loads related to power take off, mooring, device structure, and so on
    - In wind, there is not a lot of certification instrumentation available and specific design elements are not necessarily considered; typically, only global loads are measured
    - The wind industry is more developed in this area. Standard turbine architectures exist, so there is greater ability for a consistent set of measurements to be defined.
- A standard on power production definition would be very useful for WECs.

Day 2: Laboratory Testing Group Discussions

The following questions and issues were covered in the laboratory test group discussions.

- What role does laboratory and university research and testing currently play in the design process?
  - Some companies cannot undertake studies of specific components (e.g., generators). National laboratories and universities could fulfill this role.
  - General environmental studies that are beneficial to the entire industry (e.g., the University of Alaska Anchorage study that looked at the environmental effects on seals) should be funded by DOE and performed at national labs and universities
  - Labs should develop testing and instrumentation packages that can be used by developers.
- Are current testing (such as lab and open-ocean) facilities sufficient to achieve commercial readiness? Are there any facility gaps that would reduce development cost?
  - DOE has a database of hydrodynamic laboratory test facilities
  - An open-ocean test facility (similar to the European Marine Energy Center) would benefit the industry by reducing cost barriers or testing.
- If cost weren't a factor, what size tank would you prefer for testing?
  - The larger the better, but larger sizes are more expensive and time consuming.
- A wide array of tank sizes is needed to test devices at different Technology Readiness Levels (TRLs)
- Sharing of existing data could be better facilitated, even if just sharing existing facilities and their capabilities. Could be listed on the DOE website.
  - The International and Towing Tank Conference provides a list of test facilities.

Day 2: Sensor and Instrumentation Group Discussion

The following questions were addressed in the sensor and instrumentation group discussion.

- Real-time, incoming wave data (such as height and speed) would be very valuable, but there is currently no good way to measure it
- It is difficult to match flow events (e.g., a large turbulent eddy) with the corresponding change in device loading
- It would be useful to have standardized environmental measurements to characterize sites similar to the wind industry
- Development of standards would likely include a better understanding of commonly used instruments
- Standardized testing of devices would be useful (for permitting, especially), but is difficult because the devices are all so different
- Third-party laboratory or university testing of specific, common components (e.g., generators, blades, and so on) will help developers defray device development costs
- Appropriate number, placement, and specifications for load-monitoring sensors should be determined and standardized.

Modeling Track

Day 1: WEC Modeling Group Discussion

The following questions and issues were covered in the WEC modeling group discussion.

- Do we need dedicated models for each type of WEC?
  - Significant interactions change from device to device
  - Need a library of tools, each with their own specific purposes
  - A cost model that can model various types of WECs is required. Researchers can draw on wind energy experience for some components, such as power take off. Furthermore, a cost model will help lower the cost of wave energy.
- What level of model fidelity is needed to advance to commercial readiness?
  - Ideally, power predictions should be within 5%, but that would necessitate huge increases in response amplitude operator accuracy
  - High-fidelity simulations are invaluable, but ultimately, commercial readiness is advanced by conducting in-water experiments
  - Multiple levels of fidelity are necessary at various Technology Readiness Levels (TRLs), which can be achieved using different models.
- General notes:
  - Care must be taken to ensure that TRLs are objective-based rather than task-based
  - Care must also be taken to ensure that TRLs are not overly prescriptive and leave the developer room to work within the TRL structure.
- Devices should be placed in the ocean for testing as soon as possible to help researchers learn what is needed for modeling
- Some component cost models can be borrowed from other industries (such as offshore wind and oil and gas)
- Experimental data needs to be shared to allow for validation. However, companies currently place a large value on experimental data, making it difficult to obtain.
- The most feasible route for generating publicly available data appears to be the development of a "neutered machine" that has no intellectual property restraints
- Environmental data will be easier to make public because of permitting requirements
- To assist developers, DOE can utilize supercomputers to verify lower-order models; assist with resource characterization; and provide an available data set for validation.

Day 2: Current Technologies Modeling Group Discussion

- Appropriate data collection and sharing
  - When sharing measurement data, maybe wait 1 year before sharing to allow for publication
  - A baseline set of data would be good for modelers across the United States

- Publicly available data must be detailed and raw. If only integrated quantities are measured, tweaking a model to validate is easy.
- Intellectual property of data is of great concern. Because the industry is young, the data that has been developed has great value.
- Government can help by funding a project to develop baseline sets of data for turbines and WECs.

- Environmental modeling and certifying agencies
  - Certifying agencies do not consider data collected in one region to be applicable to another. What can be done about this?
    - Acoustic emissions and electromagnetic interference from cables change little from site to site. Permitting agencies should consider this.
    - Build a large body of data and show the correlation between the sites. This must be shown explicitly and clearly and will help to assuage the fears of regulators.

- How can we encourage companies to share data?
  - Lots of opposition to sharing machine data will probably be encountered. It might be possible to share environmental data or code because of disclosure requirements.
  - Data has been shared with national labs and universities using nondisclosure agreements
  - In early wind days, NREL created "neutered machines" (gutted and rebuilt) to foster collaboration on those machines and to create public data
  - Provide a financial benefit for companies to share data.

Day 2: Modeling Needs Forum

The following questions and issues were covered in the modeling needs forum.

- What capabilities do DOE and the national labs need to develop that are outside of the scope of developer capabilities?
  - Support validation by developing best practices for making experimental measurements
  - Verify lower-order models by utilizing supercomputing resources to check against higher-order models
  - Provide third-party oversight and validation for codes
  - Provide data sets to be used for validation.
- Are there other currently existing modeling capabilities that could be leveraged (from other industries, or internationally) to address MHK industry needs?
  - Operation and maintenance cost models can be borrowed from offshore wind

- Engage in activities like the International Energy Agency's Wind OC3 and OC4 to cross-compare codes?
- Draw upon experience of European certifying agencies
- Offshore wind experience in scheduling and estimating operation and maintenance is very applicable.

- If a measurement initiative with data taken at multiple field sites were undertaken, what specific suite of measurements would be desirable for the development and validation of models?
    - Suggested measurements include temperature, salinity, wave direction, wave height, full bathymetry, wildlife (location and quantity), full vertical profile (ADV and ADCP), fluid characteristics at hub height.

Day 2: Open Discussion of Industry Needs, Workshop Findings, and Closeout

The follow items were addressed during the open discussion.

- Site characterization is an area that DOE can and should develop, which will be helpful to the industry as a whole.
    - Diversity in characterized sites will allow new potential sites to be better understood by extrapolating from known information at base/reference sites
    - Will help make designs easier to fund, insure, and permit because the economics will be more standardized and transparent
    - Industry leaders seem interested in sharing data in exchange for financial support with testing.
- Bigger testing facilities are needed to more accurately test high TRL devices
- What capabilities do DOE and the national labs need to develop that are outside of the scope of developer capabilities?
- DOE should characterize wave data for many coastal sites. Wave sites can then be ready for selection when the technology is.
    - Similar to the wind process.
- Baseline environmental data. Comparable to the standards of wind energy. The framework to categorize should be based on:
    - Shoreline destruction
    - Endangered species
    - Habitat stability
    - Acoustics
    - Electromagnetic field.

- Although a good number of sites have been well-characterized, they were characterized by different companies. Therefore, successful characterization is a matter of getting different companies and agencies to cooperate and release data.
    - A device that's only been tested at a test site is not as attractive to investors; however, it could be marketable at similar sites if the sites are classified
- Are developers interested in a DOE-funded test campaign where data is made public?
    - The benefit to developers would be in helping to identify structural problems and areas of improvement. If there is a benefit, the developers could find a way to make that work.
    - If initial tests are done at viable project sites, developers could build a stronger case when selling their products.
    - A national testing center would be attractive. However, it would be important to protect intellectual property if data were to be shared.
- Regional-level resource studies are within the scope of DOE, but site-specific considerations are not as likely. DOE is not going to pick sites for developers.
    - Perhaps this should be done at established national marine test centers? Then, developers can classify the type of each site, generate a reference frame, and add new sites to that framework.
- Bob Thresher: "In the early days of wind, eight candidate sites were established and studied. Then they became reference sites. Ultimately, we didn't do a very good job because we didn't get turbulence data. Really would love to have several years of data to understand extreme events that you can't get from shorter-term studies. Seems within the realm of DOE to do this because they are trying to encourage development."
    - Hawaii, Oregon, and Massachusetts are all already well-characterized by the Navy and OSU. Perhaps we are closer to having reference sites than we think. Maybe we just pick a few more to round out our portfolio?
    - Go by geographic location. Choose an estuary, bay-to-ocean, and so on. That is exactly what the wind developers did. Europe is currently doing this.
    - After the test site, set up pilot sites at sea in real conditions.
- A strategy and a facility for testing device arrays will be needed in the coming years. Developers are not ready for this type of facility just yet, however.
- A DOE database that exists that lists laboratory testing facilities. Perhaps the database could list these facilities in a social networking platform where someone can say, "I have this scale device that I'd like to test in this way," and perhaps be able to connect interactively with the proper testing site.
    - Opportunity to post reviews and discuss facility capabilities
    - Perhaps something more along the lines of accreditation.

- What are the required testing capabilities/instruments?
  - Standardization of testing facilities, methods, and instrumentation (e.g., a data acquisition system)
  - Standardize ways of doing inflow measurements and power production estimates
  - High-fidelity instrumentation packages and protocols for measurements (especially loads)
  - Measure wave and current simultaneously
  - Work on ways to measure high-frequency loading from turbulence and improve ways to measure turbulence as it relates to device lifespan
  - Absolutely need larger testing facilities. The roadmap of TRL is also a roadmap along the scale. For each roadmap, an appropriately sized testing facility is needed (i.e., you need a bigger test facility to move further up TRL levels).
  - Measurement campaign would likely focus on more consistent measurement of existing sites instead of new ones.
- Engaging stockholders:
  - In Canada, stockholders addressed community engagement up front and continually worked with the fishermen in the area. This approach is a good model for making sure those constituencies that are very vocal will be appeased right away.
  - OSU is engaging stakeholders effectively in the Northwest.
- It would benefit the industry if DOE awarded funds that required less cost share (80:20 perhaps?) This is especially important because the industry does not yet have a cash flow. It may even be acceptable if fewer awards are made.

Appendix E: Responses to Post-Workshop Questions

At the conclusion of the workshop the attendees were asked to submit email responses to the following three questions:

1. What was your most significant takeaway from the workshop?
2. What is the most important thing that you think should be done to advance the marine and hydrokinetic industry? We are looking for your best "big idea" that would have a broad national impact in accelerating commercialization.
3. What should we do to improve future events of a similar nature?

The following table contains responses from attendees who submitted their answers via email. The responses are presented anonymously and have not been changed.

Table E1. Workshop Attendees Responses

Response 1	1. a) DOE is committed to and working very hard to accelerate this market. The environmental permitting process may still be a major cost driver that could make or break some small startup companies. b) DOE needs to establish or support some large-scale testing facilities geared toward accurate device evaluation with the goal of device optimization and impact of COE. I had several companies approach me relative to the type of testing needed to advance a device concept to a competitive and marketable device in the eyes of investors, and the cost of this type of a program relative to low-cost, proof-of-concept testing. c) It is clear that we need to establish testing guidelines that can help device developers properly test and evaluate their devices, and can help DOE and investors make intelligent evaluations of devices. We want to put investments where there will be positive payoff. 2. I think this falls into two categories: a) environmental permitting and b) cost of energy – device competitiveness a) Environmental permitting – develop accepted modeling tools by regulatory agencies that can be used to help predict environmental impact and possibly accelerate and reduce cost of permitting process. b) Development of "low-order" design/performance tools or "high-fidelity"- "higher-order" modeling tools are nice but it was not clear how these tools feed into a device overall design taking into account device optimization with the goal of reduced "cost of energy" and "long time durability." I think this is where the MHK device community needs to move in to enable competitive selling and marketing of devices. The DOE reference model program is a great step in this direction by helping to identify major cost drivers toward COE. Development of a design tool, resource, or protocol through the reference model program is a worthwhile endeavor. R&D efforts in the TRL 4-7 range of development with the goal of COE impact would be welcomed I think. 3. a) Need to get more investors involved. We need to hear from them.

	b) Try to get more input from other areas of the world – EU or Japan, for example.
Response 2	1. That some of the key learnings from wind are permeating into the MHK industry and that people are gaining an appreciation of the requirement to understand turbulent loading on the device for operational and design purposes. 2. Leverage CED to strategize and stretch public funding further – maybe even develop some United States/Canadian kit that is 'easy' to deploy, can measure turbulence at TISEC hub height, robust and resilient to the environment. Also focus (more than only half of funding) on testing – if modelers are always asking for more data for model validation… then I guess we need to get more data that is appropriate and suitable for validation. 3. The messaging was great at the start. I'd prefer not to be completely split into two streams most of the time (but I don't know a way to get into the detail discussions without that). Also, if questions should be answered, then the presenters should have those questions before, so that they can tailor their presentations to get people thinking in the right direction (or they can attempt persuasion and influence) and the chairs of the sessions should review the questions prior to the presentations starting – so that the questions are in everyone's mind as they are listening to the questions.
Response 3	1. Familiarity with the benefits of how infrastructure like the NWTC could be paralleled to boost development in marine energy: imagine well-characterized benign wave and tide test sites at nominal cost for developers in all disciplines that could accelerate development through shared "lessons learned" and (nonproprietary) data. 2. Developers face the challenges of large financial cost, long time, and major risk in taking a device from the prototype phase to commercial. Due to the inherent intermittency and remoteness of marine energy, there is a huge gap between a device that produces power and a device that is integrated with a grid. Interconnecting marine energy sources with storage and transportation technologies is one way to ensure marine energy is desirable and competitive. 3. a) Understanding that it is like herding cats to run an event of this size with volunteer chairs, I think it would work better if the chair gave their presentation at the end of their session to add motivation for keeping things running on time. You may have done this, but presenters should be strongly urged to limit their presentation to, say, one slide per minute, as some were getting into far too much detail. The organizer should mention in the opening talk (with humour) that they will be reminded to end their presentations on time, so the chairs don't feel like the "bad guys". b) Having two tracks was frustrating for some. I was there representing an institute that is interested in both modeling and testing. It might be better to

	have a longer (3-day) workshop with 1 or 2 days on the one topic, followed by the other or mornings on modeling, afternoons on testing. A space for coffee and networking would let people break out from sessions that aren't pertinent while still getting value for their time. c) While there were opportunities for discussion in the large group, not everyone spoke up. You could try running sessions where attendees are divided into randomized five to six-person groups for 20-30 minutes to answer a question, and then have one from each group give their summarized answer(s) to the note takers.
Response 4	1. The model testing in basins would be improved with a set of uniform guidelines for the industry. A good starting point would be using: a) The International Towing Tank Conference (ITTC) has at least one guideline for the testing of wave energy converters. There may be several other guidelines that may be applicable. b) The International Association for Hydraulic Research (IAHR) has done work in the area of model basins. This was a large project where standards were testing in several basins. 2. A full-size testing facility would be helpful to the industry. This provides a uniform test location providing confidence to the end users. The facility could be used to provide data to optimize device for use at alternate locations. This is becoming an issue for the international community.
Response 5	1. Still much needs to be done to accurately measure and predict the loads on the devices. Much development is required for useful inflow characterization. 2. Develop a national system of test facilities where devices can be tested in increasingly realistic conditions at an increasingly realistic size. At these facilities, experts from national laboratories can assist the companies with their issues and use the lessons learned to benefit the entire industry. 3. Do not separate tracks as interaction between testing and simulation folks is critical to solving these challenges.
Response 6	1. Provide project/program funding opportunities to better determine the interactions of tidal and river environments with MHK devices that will ultimately determine their ability to be operated in a sustainable and economic fashion. This will also lead to development of ancillary support technology (e.g., fish, turbulence, debris, sediment, and performance of anchoring devices). Such program funding would allow for the collaboration of teams of experts with MHK developers and state energy organizations. 2. Support development of mobile test platforms (modular instrumented barges) that can be taken to specific locations (as opposed to a dedicated test center) that can accommodate instruments and may well support devices for testing as well (e.g., maintaining station over deployed

	subsurface devices, act as a working platform for deploying instruments and house recording and analysis equipment.
Response 7	1. Forward control (using upstream flow or wave information) is much closer to reality than I thought. This raises a big challenge in measurements: how to provide deterministic (time domain) flow or wave information to an MHK device. 2. Long-term investment in test/reference sites. Less DOE cost share requirements. 3. More cross-pollination of modeling and instrumentation/testing, perhaps separating by wave and tidal for part of the meeting (but not all!)
Response 8	1. The group of people that really understands the issues in developing computational tools for this industry is pretty small. Measurement issues are better understood and will not require any significant technological advances. 2. MHK technology's fundamental issue is that it is too expensive and immature today. Neither solely focusing on deployment or R&D will yield a long-term competitive industry. So DOE as a funder of this emerging sector will need to carefully balance these two aspects and ensure that if we do fund at-sea deployment, that the learning can be broadly disseminated to further the industry as a whole. Furthermore, the answer is a bit different, depending on what resource we are discussing and except for wave energy we do not know if these resources will be able to make a significant contribution to the energy supply portfolio of the United States. I will focus on R&D and in particular what modeling can do to advance wave energy conversion. Fundamentally, the main issues from an economic point of view are: a) Limited understanding of structural loads leading to structural overdesign b) Poor performance due to suboptimal control strategies being used on WEC devices c) No clear understanding of what the 'optimal' technology platform is for WEC d) The development timelines for WEC devices have historically been on the order of a decade. This is not sustainable for a commercial development pathway and shortening this development cycle is critical if we are to speed up the process. The fundamental challenges that need to be addressed to overcome the above issues are: e) Development of tools to evaluate loads and performance of WEC machines efficiently and accurately f) Development of tools to evaluate the cost and economics of WEC machines efficiently and accurately g) Development of optimal control strategies for different WEC configurations

	h) Wave forecasting on the 20-second time-horizon to implement advanced tuning configurations (requires addressing wave measurement and coupling with wave propagation model) Using the above toolbox of tools, we would be able to evaluate different technology platforms and evaluate them rapidly (within weeks, not months or years). The know-how to address the above challenges is available in industry and universities, but the main issue is that these are typically research codes and not engineering tools. So the question really is: how do we create an economic incentive to spur the development of these tools to allow for rapid progress to be made? These economic incentives do not need to be big, but they do need to allow the researchers to: (1) protect their long-term investments in tools and know-how they have developed, and (2) provide sustainable funding for continued development of these tools. Recruiting and retaining the right people with the right know-how will be critical in this process, otherwise we are just expending money on re-creating what others have already done. 3. Cost and economic modeling was completely missing. I would suggest that developing the proper cost functions is about as important as developing performance and cost models and critical to optimize any system.
Response 9	1. a) Gathering good experimental data is a major challenge at this point. b) Environmental permitting issues are a problem for a nascent industry. Permitting issues are especially frustrating when only a single (often small-scale) device is being deployed for testing. 2. Develop a set of performance and loads measurements from the experimental test of a characteristic set of wave and tidal energy devices. Make these data sets available for public release. In addition, release all the specifications for the devices on which the measurements are made. Providing this data set and device specifications to the public would allow industry, academia, and the national labs to develop and validate design tools (numerical and analytical) that are needed to improve device designs. In addition, many unknown design issues may be revealed while performing the experimental tests. 3. Breaking into small groups at the end of the workshop to answer the facilitated questions would probably result in more coherent answers and encourage more people to voice their opinions.
Response 10	1. I need to learn more about the impact of turbulence on life and performance. 2. Without a doubt the best market acceleration the DOE can provide is to create the market and buy our electricity. The federal government is one of the largest single users of electricity and yet the federal government has not entered into any significant agreements to buy hydrokinetic power. Agree to buy hydrokinetic power at premium rates for pilot-scale projects. If we took \$20 M (same as was given to ORPC in Maine and OpenHydro in Ireland) and directed it to 20-year PPAs at a target of \$0.20/kWh, that

	$20 M would buy 100 million kWh directly. If the money only paid the difference between market rates and $0.20/kWh, it would buy 167 million kWh (assuming $0.08/kWh U.S. average, but it would subsidize less in Alaska and more in Louisiana). If that amount was invested annually then it would be enabling 42,000 kW capacity to be installed and operated! The incentive could be ratcheted down over time or be steady for X years and then phased out. If instead, the $20 M was spread over 20-year PPAs, it would still support 2,100 kW of early stage commercial introduction (almost 10 times what ORPC is planning with their pilot and two times what Verdant is planning with the final phase of their pilot). Even a single $20 M investment would enable several businesses to get kicked off. The issue that the federal government doesn't seem to understand is that there is plenty of private capital out there and large multinational manufacturing companies willing to partner. We don't need your money for the technology. We need your money to create the initial market. We recently lost a significant JV partner and it had absolutely nothing to do with technology; it was all about the lack of market price. This same program can/should be extended to the DOD, of course. The second best thing the DOE can do is walk around the corner to the FEMP office and educate them about hydrokinetics. Every assessment that FEMP does should include hydrokinetics. No federal facility should be considering renewable generation without considering hydrokinetics on equal footing. Last time I talked to FEMP they were woefully uninformed about hydrokinetics but were definitely interested. 3. The tracks should be separated by wave and tidal; not by modeling and measuring. Also, the event should be in Boulder even at higher costs (or hold the meetings in a school classroom in Boulder), so folks can go out without getting in a car.
Response 11	1. The MHK community is small, but dedicated. Perhaps the size of the community is an advantage at this point, since the researchers were very open with ideas. At this embryonic stage of the industry, this community spirit is critical. I think this workshop helped to coordinate the efforts of the teams, in this research-oriented stage of the MHK industry. 2. I believe the existing devices, developed largely through inspiration and build and test strategies, are simply not cost effective enough. However, through modern simulation-based design and design-optimization methods, I think we can delve more efficiently into the design space. A strong suite of rapid-prototyping computational tools will also allow for inventors to quickly rank their concepts. This will help eliminate dead-ends and push developers to more innovative concepts that show promise. The open discussion within the sessions is critical, with an agenda or larger list of questions to help focus discussion. The efforts of the organizers to allow for time and to offer some questions to the floor were great, but I think this could be extended even farther. Perhaps publish a

	discussion agenda and look for questions from participants that can be vetted by email before the meeting. 3. I also think it was useful to have some perspectives in similar fields of interest, for instance the design community in the U.S. Navy or alternative energy fields outside of MHK. This cross-fertilization can lead to some interesting connections and sharing of resources.
Response 12	1. There still needs to be much more communication between the modelers and the experimentalists in order to better understand what one another need, and what capabilities are realistic/feasible. 2. Specifically for WECs, testing infrastructure is absolutely necessary to support the wave energy industry. This is an entirely new technology that doesn't have the direct analogy to wind like tidal turbines do, and there isn't an adequate knowledge base or computational capability to design devices for survival in the harsh ocean climate (and for extreme events) with any amount of confidence. In order to ensure successful deployments and development towards commercialization, the testing infrastructure throughout all TRLs must be available in the United States. This will allow developers to test their devices adequately and gain the knowledge necessary to ensure successful deployments. 3. My understanding of this workshop was to emphasize the need for discourse between testing/instrumentation and modeling, because the two areas need to support one another, however, the way the program was set up, specifically for wave energy, relevant instrumentation and modeling talks were scheduled concurrently in different rooms. Meaning people could not attend all relevant topics for their field, and often discussion was limited due to the fact that many of the knowledgeable people were in the other room. In the future, tracks should not be divided by instrumentation and modeling, they should be by current, tidal, and wave so that people can attend all relevant presentations, and discussion will include everyone in the field. Also, the attendance by industry was much higher this year than last which is a huge improvement, but generally speaking, the more people from industry in attendance, the better.
Response 13	1. The most significant takeaway from the workshop was a significant disconnect between the excellent research and advancement efforts at universities and national labs and the real-life needs of the U.S. MHK industry at the developer level. The gap—largely funding and the immediate need for relevant support of projects at or near the TRL 5/6 and 7/8 levels—is apparent. The research agenda should be more focused on developers' needs, particularly engaging more developers at these meetings. 2. The most important focus to have broad national impact on accelerating commercialization of the U.S. MHK industry would be directed support of approved pilot projects at or near TRL 7/8, at the in-water stage, to advance

	technical understanding in three specific areas: a) Longevity and reliability– advancing predictive models for loads and survivability b) Cost-effect techniques– testing, manufacturing, environmental instrumentation, installation, and O&M (coatings, corrosion, etc.) c) Environmental compatibility– support for monitoring instrumentation to satisfy approved pilot project adaptive management plans All three of these areas are critical to advancing the industry to the private investment and regulatory communities as they will continue to reduce perceived risks of the renewable technology. 3. To improve future events, Verdant Power suggests: a) Separate tracks by wave and tidal technology instead of modeling and experimental b) Encourage panels to focus on the "objectives of research" and the relevance to the industry today c) Engage more MHK developers to hear their specific needs and how the R&D community can respond with both applied testing and research.
Response 14	1. The MHK sector has progressed significantly in the United States during the last couple of years, and there is a lot of good work being done. Yet limited resources are available for encouraging the growth of this new industry, and they must be used wisely and collectively and not to undertake low-priority studies or to repeat work already done elsewhere. Collaboration both nationally and internationally will be key. 2. A clear, consistent, and committed energy policy that recognizes the need for a diversity of energy sources and therefore provides a firm basis for investment decisions in a range of technologies. The policy must take account of the fact that the technologies required to sustain long-term energy requirements will be at different TRLs and therefore require different levels of support. MHK projects have significant development times, and an effort should be made to limit uncertainties in the support that can be expected in the coming years to give investors' confidence that support for MHK will not suddenly disappear in the year(s) following their initial investment. 3. It would be great to further encourage industry/commercial involvement at the workshop.