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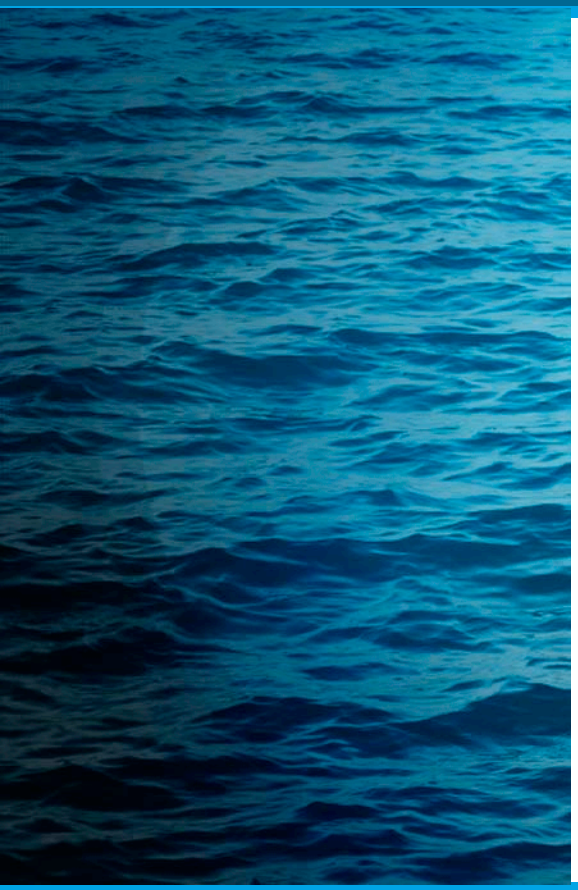

Purpose: To accelerate marine energy development and deployment

Approach: Develop the essential engineering and design tools, methods, and testing capabilities

Objectives: Provide the MHK industry the tools needed to reduce cost, increase device energy capture, and to lower deployment risk to penetrate the electricity marketplace

NREL - FY09 Lab Call: Supporting Research and Testing for MHK

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National Renewable Energy Laboratory

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Nov 2, 2011

Outline

- MHK Technology Roadmap - Challenges
- NREL Lab Call Efforts in Context of MHK Portfolio
- Integrated Technical Approach
- Project Focus Areas
  - Instrumentation
  - Testing Protocols
  - Design Tools – Current
  - Inflow Characterization
  - Design Tools – Wave
  - Test Facility Support
  - OTEC
- Budget and Schedule
- Publications

Overview of the Industry's Challenges
(From the U.S. MHK Technology Roadmap)

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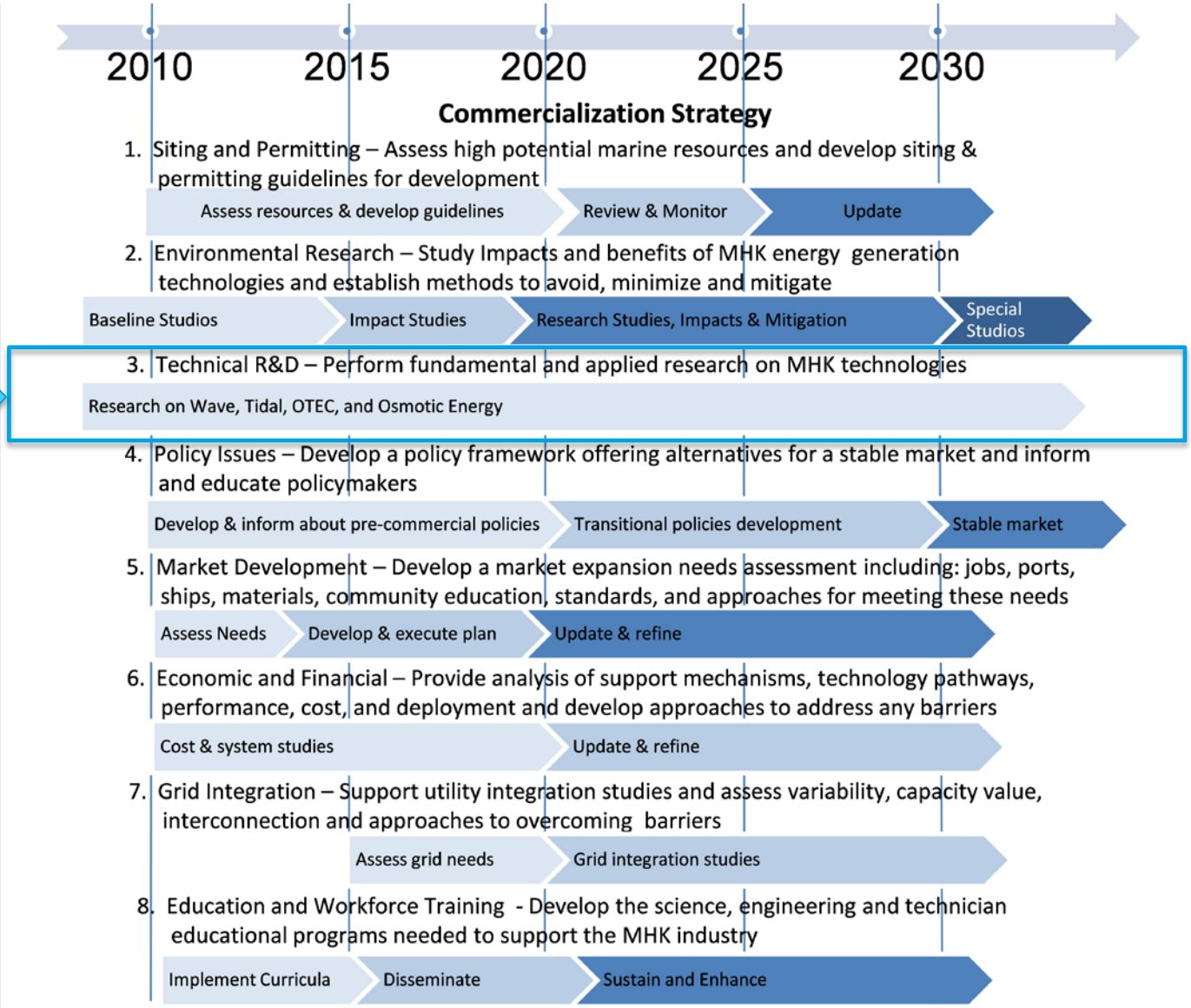
NREL Lab Call Focus



NREL's MHK Portfolio

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Marine and Hydrokinetic Technologies

Industry Support
- Verdant Power
- Principle Power
- TRL FOA Projects

Technology Assessment
- Technology Roadmap
- Testing Infrastructure Strategy
- Standards Development
- Reference Models
- Cost Analysis

Design Tools
- Tidal, Ocean, and River Systems
- Wave Energy Systems
- OTEC

Testing
- Instrumentation
- Lab and Field Testing Protocols
- Test Facility Support
- In-Flow Characterization

Resource Assessment
- River Current
- Wave
- OTEC

Market Analysis and Economic Development
- Jobs and Economic Development
- Industry Outreach

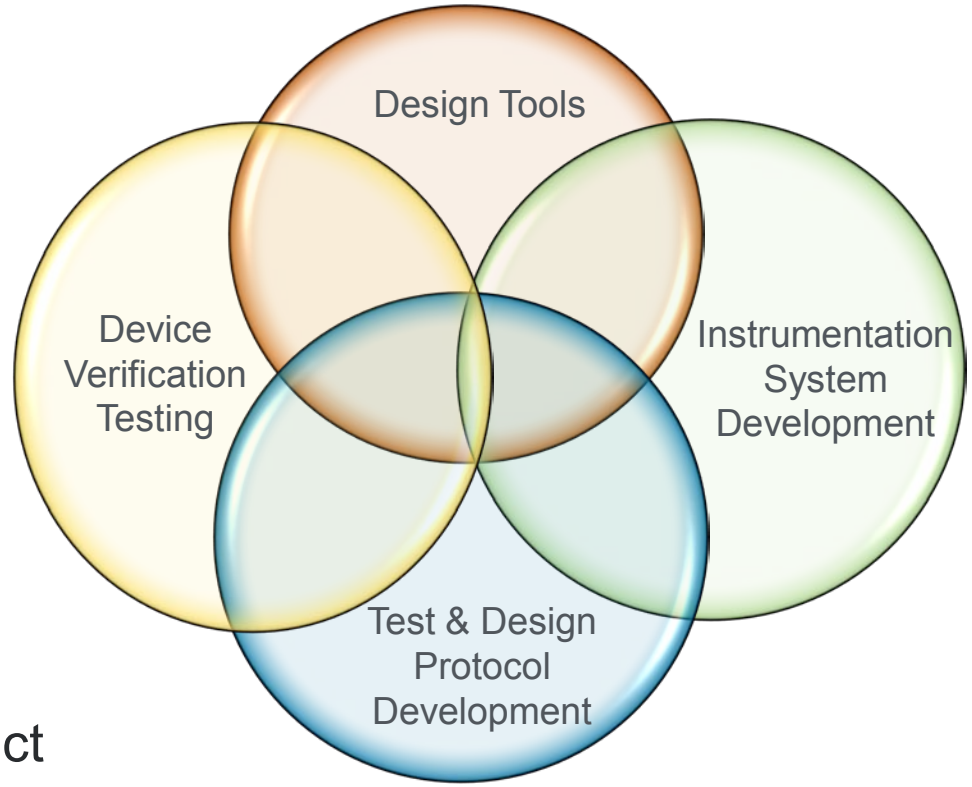
NREL Lab Call Efforts

Lab Call Partners:

ORNL, PNNL, SNL, HINMREC, NNMERC, SNMREC, MIT, OSU, PSU, UCinci, NAVFAC, OHMSETT, and others

Lab Call Integrated Technical Approach

- Integrated approach provides industry with open source and validated design tools
- Develops instrumentation and testing protocols for the use of industry and National Marine Testing Centers
- Supports DOE demonstration projects by providing instrumentation and protocols
- Subscale and full scale test project results provide further data for model improvement



Instrumentation Development

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Objectives

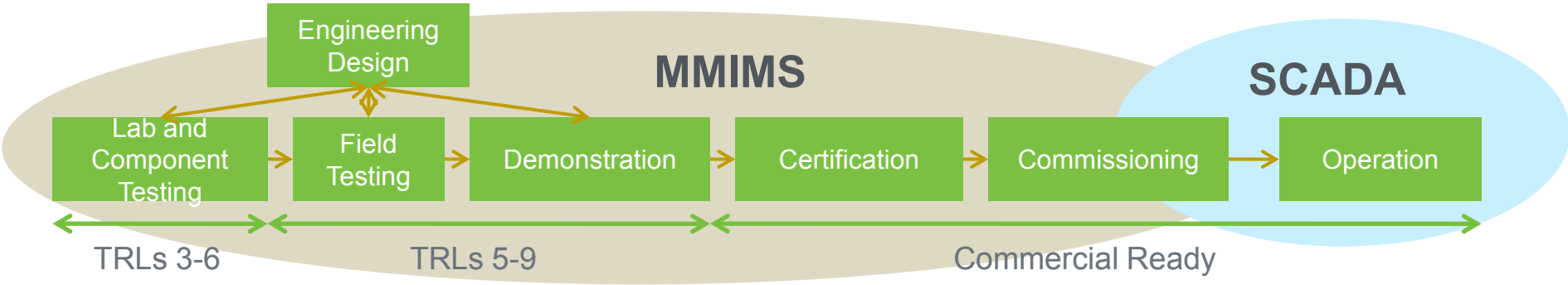
- Develop a modular instrumentation system for laboratory and field data measurement
- Disseminate hardware layout/design and software
- Deploy system for in-water research, testing, and evaluation of MHK technologies

Products and Deliverables

- Modular Marine Integrated Measurement System (MMIMS)
- Submerged Fiber Optic Measurement Package
- Final design report and all schematics
- Software source code (MMIMS)
- Moored Turbulence Measurement Package Prototype
- MetOcean and device performance data
- Established instrumentation users group

Approach

- Systems engineering to ensure useful product
- Leverage existing systems and know-how developed by the DOE wind program
- Leverage internal marine specific operations and instrumentation experience
- Active integration of users to guide design and implementation (Instrumentation Working Group)
- Partners – NAVFAC, HINMREC, NNMREC, SNMREC, ORNL, PNNL, SNL, UNH, Cardinal Eng., and others



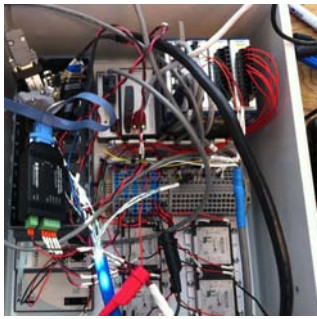
Instrumentation Development (Cont.)

Major Accomplishments

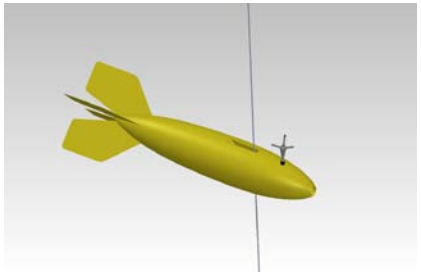
- Established MHK instrumentation working group
- Held 1st Advanced Marine Renewable Energy Instrumentation Experts Workshop
- Completed detailed design of the MMIMS hardware and software
- Initial hardware prototype MMIMS assembled and code development started
- Completed architecture of the Moored Turbulence Measurement Package

Future Milestones

- Deploy MMIMS to support several device tests in partnership with industry to support field testing and refine the MMIMS
- Complete development of core software
- Release hardware design and software source code
- Complete development of structural, metocean, and power performance modules of the MMIMS, including design reviews



MMIMS Prototype



Moored turbulence package

Challenges

- Marine instrumentation is very expensive, making it challenging to acquire sufficient hardware to support simultaneous development/test deployments

Testing Protocols

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Objectives

- Develop protocols for laboratory and open-ocean wave and water current testing that are relevant to and conforms with U.S. technology development and practices

Approach

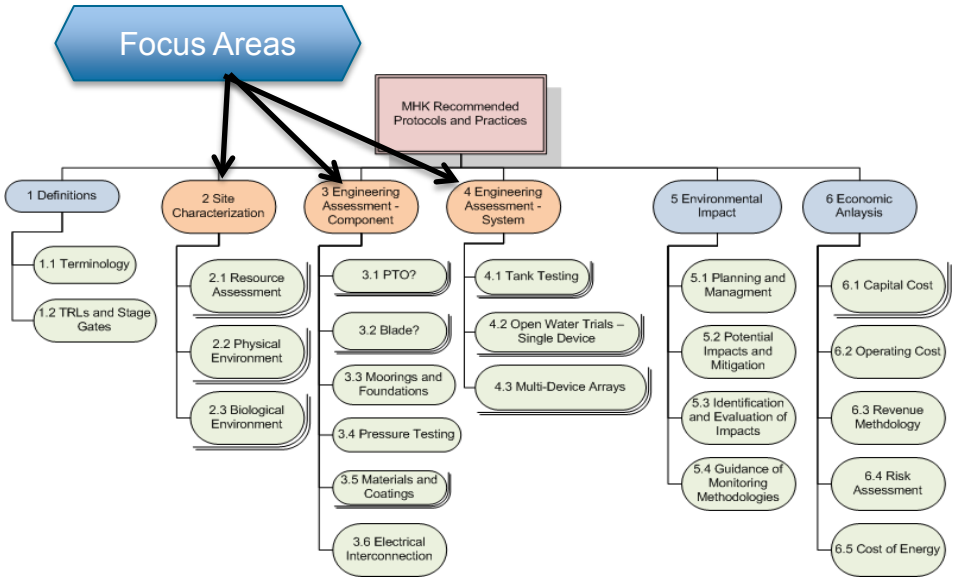
- Build upon protocols from wind, the marine industry, and MHK efforts in Europe (EMEC, Equimar, etc.)
- Integrated team (Protocols Working Group) of MHK experts from industry, national labs, and academia developing protocols in their areas
- Partners: OHMSETT, NNMREC, SNMREC, HINMREC, ORNL, PNNL, SNL, UHN, Cardinal Eng., and others

Products and Deliverables

- Recommended protocols and practices for wave and current (river and tidal) component and systems testing and site characterization (priority for in-water testing)

Major Accomplishments

- Established MHK Protocols Working Group
- Assembled and reviewed library of MHK testing protocols from EMEC and Equimar
- Developed WBS for U.S. recommended testing protocols and practices
- Developed outline for NNMREC testing protocols



Current Energy Converter Design Tools

Objectives

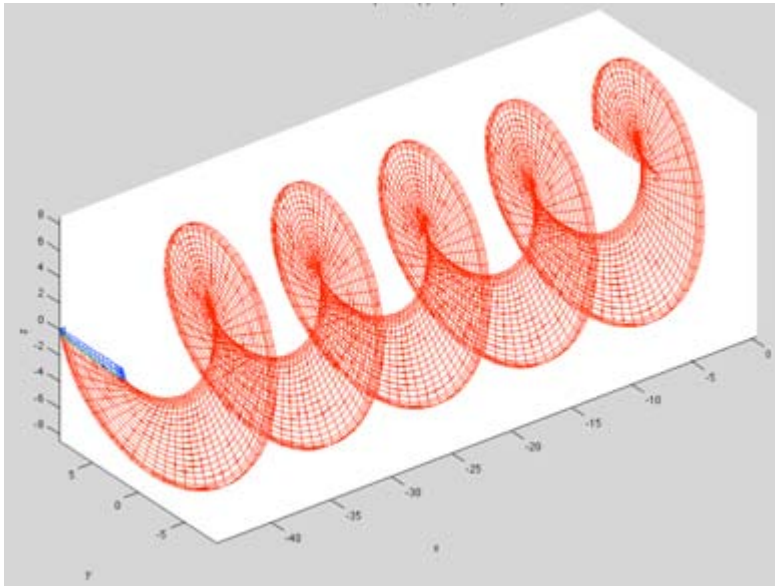
- Develop tidal, river and open-ocean current energy converter computer aided design tools for horizontal axis and cross-flow turbines – inflow, wake, component, system (single device) and array to enable design optimization (performance and loads)

Products and Deliverables

- Public domain source code, documentation and example applications: (e.g. Harp_Opt, TurbSim, Dynamics code)
- Publications to disseminate code information
- Utilize codes to support Marine Energy Design Assessment project (Reference Model)

Approach

- Leverage experience with wind turbines to accelerate tidal device computational tool development
- Adapt existing wind codes for MHK application (e.g. Harp_Opt, TurbSim, FAST)
- Utilize modular architecture and open source software to enable rapid development, ease of customization, and code sharing
- Utilize wind experimental expertise to develop protocols and instrumentation to validate tools
- Adapt wind turbine array simulation tools for application to water current device arrays
- Utilize CAE tools to design and evaluate devices and improve turbine performance and reliability
- Partners – PSU, UCinci, SNL



Horizontal Axis Turbine Wake Simulated with Vortex Method

Current Energy Converter Design Tools

Major Accomplishments

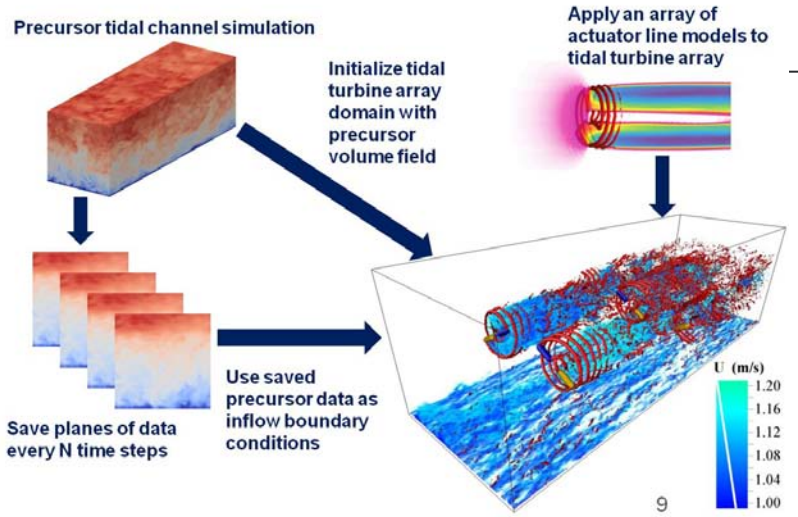
- Hosted 1st DOE Modeling and Simulation Experts Workshop and completed draft report
- Developed current turbine performance code with improved calculation speed (WT_Perf)
- Implemented integrated actuator-line method into LES to simulate MHK turbine array
- Code website for water power code sharing and discussion: http://wind.nrel.gov/designcodes

Future Milestones

- Integrate free-wake method into FAST to simulate the hydrodynamic effects more accurately
- Develop free-wake codes for both horizontal and vertical axis turbines
- Integrate added mass into wind turbine code for MHK application (FAST)
- Adapt structural code (PreComp) for marine current applications
- Improve the Harp_Opt optimization algorithm
- Improve code capability of handling axial flow turbines with ducts

Challenges

- Need experimental data to validate codes
- Balancing immediate needs to obtain results for reference model with developing improved modeling tools
- Need range of turbulence measurements from a variety of sites to estimate turbulence induced loads for marine current turbines (need more data)



LES Simulation Of Tidal Array

Tidal Inflow Characterization – PNNL

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Objectives

- Characterize turbulent water inflow conditions before and after the deployment of prototype Tidal turbines
- Input into the development of field instrumentation packages and develop analysis protocols

Approach

- Participate in river inflow characterization laboratory and field testing

Products and Deliverables

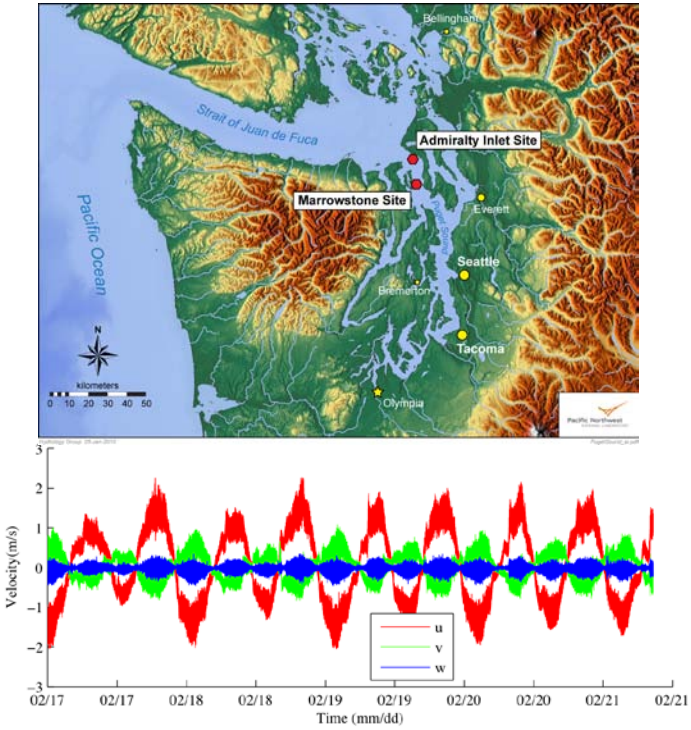
- Data sets of tidal inflow conditions
- Protocols for measurement and analysis of inflow data

Major Accomplishments

- Deployment and retrieval of tidal turbulence instrumentation package at the Marrowstone Island test site (22 m depth) in FY10 and FY11 (partner: NNMREC – UW)
- Performing advanced time-series analysis to look at coherent turbulence
- Checked field data from the Spring 2010 and 2011 Marrowstone Island site that was delivered to NREL

Future Milestones

- Plan for deep water deployments in Puget Sound
- Distribute data and publish results



Challenges

- Measurements over the full depth range (4-12 m) of rotor sweep
- Wake characterization for deployed MHK devices

Funding

- $200k (FY10); $200k (FY11) $160k (FY12)
- $190k costed to date

River Inflow Characterization - ORNL

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Objectives

- Gather field and laboratory data for inflow characterization
- Develop protocols for measurement and analysis of inflow data

Approach

- Participate in river inflow characterization studies: laboratory and field testing

Products and Deliverables

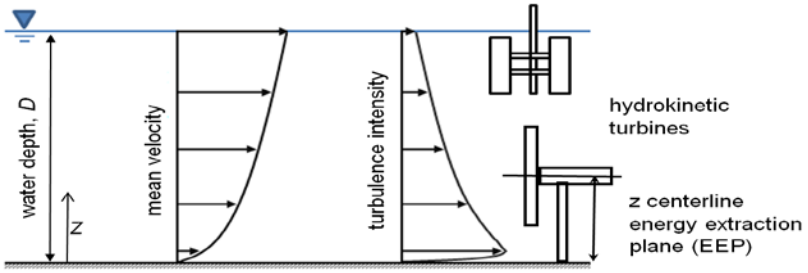
- Data sets of river inflow conditions
- Protocols for measurement and analysis of inflow data

Major Accomplishments

- Laboratory and field measurements for model validation, including profiles of mean velocity, turbulence intensity and spatial coherence
- Processed data and developed characteristic inflow profiles

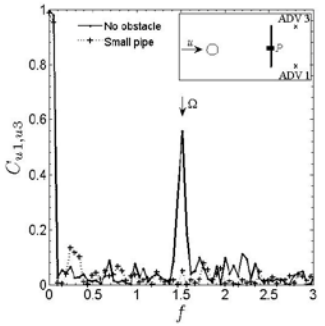
Future Milestones

- Complete inflow characterization study at Verdant site
- Distribute data to NREL and SNL modeling teams



Inflow characterization for MHK turbines, schematic (Neary et al. 2011)

ORNL Synchronized ADV Array in SAFL Main Channel



Spatial Coherence Measured with ADV array

Challenges

- Synchronized ADV measurements at RITE delayed two years by site permitting issues with USACE

Wave Energy Converter Design Tools

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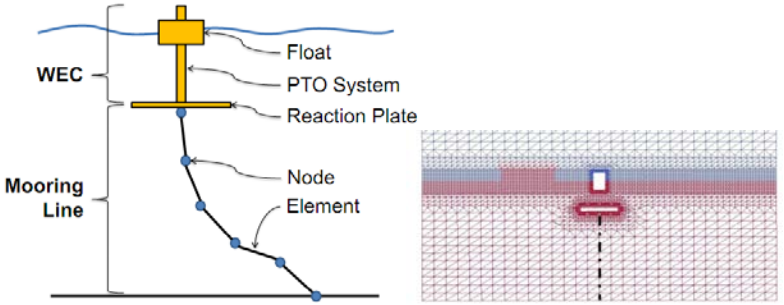
Objectives

- Develop wave energy converter Computer Aided Engineering design tools for point absorber, attenuator, oscillating water column, and surge technologies – metocean, component, system (single device) and array
- Perform model to model verification and participate in laboratory and field testing to gather validation data
- Develop device survivability and reliability design methods
- Develop wave device/array optimization methods and control strategies

Products and Deliverables

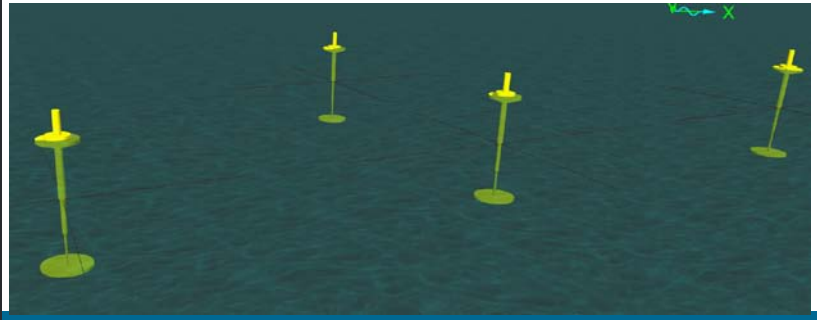
- Comparison of commercial code predictions with experimental data (wave tank and full scale)
- Use in Marine Energy Design Assessment (Reference Model) project
- Public domain source code, documentation and example application for several different modeling methods (e.g. parametric, boundary element, and CFD)
- Publications to disseminate code information



Mooring Line Design

Approach

- Assess utility and limitations of commercial codes (e.g. OrcaFlex™, Star CCM+™, ANSYS AQWA™)
- Develop custom codes balanced for speed and computational accuracy
- Utilize a modular architecture and open source software to enable rapid development, ease of customization, and code sharing
- Validate codes with laboratory and field data
- Utilize tools to evaluate/design WEC performance and reliability/survivability
- Partners: MIT, OSU, SNL



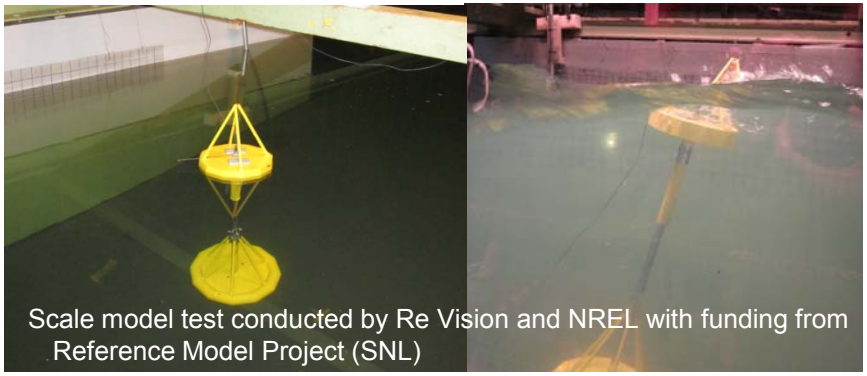
Wave Energy Converter Design Tools (Cont.)

Major Accomplishments

- Held 1st Modeling and Simulation Experts Workshop and Completed Report
- Developed model of a two-body single point absorber using OrcaFlex™ to predict energy capture and compared with wave tank data (to be published)
- Developed CFD single body extreme wave simulation
- Used simulations to run extreme wave and power production simulation (Point Absorber Reference Model) and support wave tank validation testing
- Integrated a single point absorber model with mooring line dynamics code into an open-source CFD code
- Assessed the limitations of first-order solutions (OrcaFlex™) with higher-order CFD solutions (Star CCM+™) for wave-body interactions

Future Milestones

- Compare performance using first-order modeling of wave devices with higher-order CFD models
- Develop Boundary Element Method code for optimizing the form of wave energy devices
- Explore extreme events and reliability of WEC systems (OSU)
- Explore approaches for coupling structural dynamics and RANS fluid models
- Develop wave array system optimization and control algorithms (MIT)



Scale model test conducted by Re Vision and NREL with funding from Reference Model Project (SNL)

Challenges

- Balancing immediate needs to obtain results for reference model with developing improved modeling tools
- Limited resources to support field and laboratory tests to validate models

Test Facility Support

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Objectives

- Assist National Marine Renewable Energy Centers in the design, development, and implementation of U.S. MHK test facilities

Approach

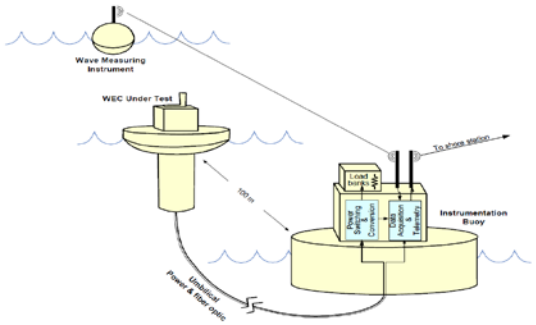
- Assist in the development and utilization of testing plans, protocols, instrumentation, device performance codes, and American Association for Laboratory Accreditation (A2LA)
- Provide technology design reviews and evaluations
- Leverage NREL wind and marine expertise and experience

Major Accomplishments

- Reviewed and provided NNMREC written feedback on their testing facility plans, including the MOTB and fixed site facilities
- Provided grid mimic solution for MOTB to OSU
- Feedback on Dynamometer testing protocols to SNMREC

Future Milestones

- Continue to assist national testing facilities
- Integrate MMIMS with NNMREC WEC measurement systems
- Provide design feedback on the new MOTB design
- Continue to assist SNMREC with test plans and protocols, instrumentation system development, etc.
- Continue to work with HINMREC to define additional priority collaboration areas



NNMREC MOTB

Products and Deliverables

- Testing protocols
- Instrumentation systems

Challenges

- Overcoming inefficiency of developing collective work products remotely

Ocean Thermal Energy Conversion (OTEC)

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Objectives

- Assess state of the art for the various technologies relevant to OTEC development and deployment
- Identify research directions which could result in lower overall OTEC system costs

Approach

- Assess current status of OTEC in terms of performance, cost, and environmental constraints using existing NREL expertise, industry contacts, and the literature
- Utilize experience and knowledge of OTEC systems and relevant industry resources to establish a compendium of required components and materials for open- and closed-cycle OTEC along with research directions that could aid in lowering the overall system costs

Products and Deliverables

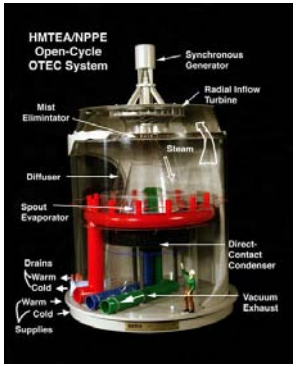
- A compendium of required components and materials for open- and closed-cycle OTEC
- Draft of research directions that can aid in lowering the overall system cost for advanced OTEC systems

Major Accomplishments

- "Staging Rankine Cycles Using Ammonia for OTEC Power Production." Bharathan, D. NREL Report No. TP-5500-49121.

Future Milestones

- End of FY12: Compendium of required components and materials for open and closed-cycle OTEC
- End of FY12: Draft assessment of research directions that can aid in lowering the overall system cost for advanced OTEC systems



NREL Lab Call Team

Personnel	Notes		
Desikan Bharathan	• 25+ years of OTEC experience	• Ph.D. Aerospace Engineering, University of Virginia	
Rick Driscoll	• Principle Investigator for broad portfolio of theoretical and applied ocean engineering projects	• Ph.D. Mechanical Engineering and Physical Oceanography, University of Victoria, B.C. • Founding Director, Cntr. for Ocean Energy Tech., FAU	
Ye Li	• Modeling Principle Investigator	• Ph.D. in M.E. from University of British Columbia, Thesis on tow tank testing of vertical axis water turbines	
Al LiVecchi	• Program Integrator/Senior Project Leader	• 20 years experience in technology management • M.B.A Cornell, M.S. BioEng., Clemson, B.S. M.E., Lehigh	
Pat Moriarty	• Senior Engineer – Array modeling, turbine design	• Ph.D. Aeronautical Engineering, Stanford University	
Walt Musial	• Group Manager, Offshore Wind and Ocean Power Systems	• Initiated Development of NREL's Structural Test Facilities and Dynamometer Test Facility	
Eric Nelson	• Ocean instrumentation, data acquisition, and ocean deployment	• Formerly at Monterey Bay Aquarium Research Institute	
Bob Thresher	• Research Fellow	• More than 35 years of research, development, engineering, and management experience	
Arielle Wolfe	• Business Support for Offshore Wind and Ocean Power Systems Group	• B.S. Cornell University	
Post Doctoral Students	• Matt Churchfield, Ph.D. Aeronautical Engineering, Purdue University • Levi Kilcher, Ph.D. Physical Oceanography, Oregon State Univ.	• Marco Masciola, Ph.D. Mechanical Engineering, McGill University • Yi-Hsiang Yu, Ph.D. Civil Engineering, University of Texas - Austin	• Michael Lawson, Ph.D. Mechanical Engineering, Penn State University
Vincent Neary (ORNL)	• Lead for ORNL's MHK technologies research and development activities	• Ph.D. Civil and Environmental Engineering (Hydraulics), University of Iowa	
Marshall Richmond (PNNL)	• Chief Engineer of Hydrology Group	• Ph.D. Civil and Environmental Engineering, University of Iowa	

Plan, Schedule, & Budget

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Schedule:

- Initiation date: Funding received September, 2009. Work Initiated October, 2009.
- FY 2012 is the third year of three year lab call funding
- Milestones discussed on previous specific project area slides

Budget:

- As of end of FY 2011, 72% ($2,951k) has been costed
  - Does not include FY12 funding
  - Does not include $326k of commitments in place
- FY 2012 funding of $1,707k
- New effort starting in FY10: required some time to ramp up the team and establish partnerships – resulting in spend plan shifted towards 2nd half of 3 year lab call effort

NREL Budget History (Agr. # 20067 and 20069)

FY2009		FY2010		FY2011	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$2,163k	$0	$239k	$0	$1,707k	$0

Above is Funding to NREL. Additional Funding for Projects:

- Navy/Naval Facilities Engineering Command – Inter-Agency Agreement (IAA) $100k (FY10), $50k (FY11), $50k (FY12)
- Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) Ohmsett Facility - IAA $100k (FY10)
- ORNL, PNNL, SNL also funded for associated efforts

Publication Examples

- "**1st Marine and Hydrokinetic Device Modeling Workshop: Final Report"** ; Li, Y.; NREL Report No. TP-5000-51421; DOE/GO-102011-3374.
- **"1st Advanced Marine Renewable Energy Instrumentation Experts Workshop Report"**, R. Driscoll, MP-5000-51584.
- **"A Large-Eddy Simulation Study of Wake Propagation and Power Production in an Array of Tidal-Current Turbines"** – Authors Matt Churchfield, Ye Li, and Pat Moriarty – presented at the 9th European Wave and Tidal Energy Conference, 2011, Southampton, England, September 4-9, 2011. NREL/CP-5000-51765.
- **"Development and Verification of a Computational Fluid Dynamics Model of a Horizontal-Axis Tidal Current Turbine"** Lawson, M.; Li, Y., Sale, D. – presented at the 30th International Conference on Ocean, Offshore, and Arctic Engineering, Rotterdam, The Netherlands, June 19-24, 2011. NREL/CP-5000-50981
- **"Structural Design of a Horizontal-Axis Tidal Current Composite Blade,"** Bir, G., Lawson, M., Li, Y - presented at the 30th International Conference on Ocean, Offshore, and Arctic Engineering (OMAE) in Rotterdam, Netherlands, June 19-24, 2011. NREL/CP-5000-50658
- **"A RANS Simulation of the Heave Response of a Two-Body Floating-Point Wave Absorber"** – Yu, Y. and Li, Y. – presented at the 21st International Offshore and Polar Engineering Conference, Maui, Hawaii, June 19-24, 2011. NREL/CP-5000-50980
- **"Developing an Instrumentation Package for In-Water Testing of Marine Hydrokinetic Energy Devices."** Nelson, E. [Proceedings] Oceans 2010, 20-23 September 2010, Seattle, Washington. Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEEE) NREL/CP-5000-50249
- **"Staging Rankine Cycles Using Ammonia for OTEC Power Production."** Bharathan, D. NREL/TP-5500-49121.
- **"Investigating the Influence of the Added Mass Effect to Marine Hydrokinetic Horizontal-Axis Turbines Using a General Dynamic Wake Wind Turbine Code."** Maniaci, D.; Li, Y. ; NREL/CP-5000-52306.
- **"Hydrodynamic Optimization Method and Design Code for Stall-Regulated Hydrokinetic Turbine Rotors."** Sale, D.; Jonkman, J.; Musial, W. NREL Report No. CP-500-45021.