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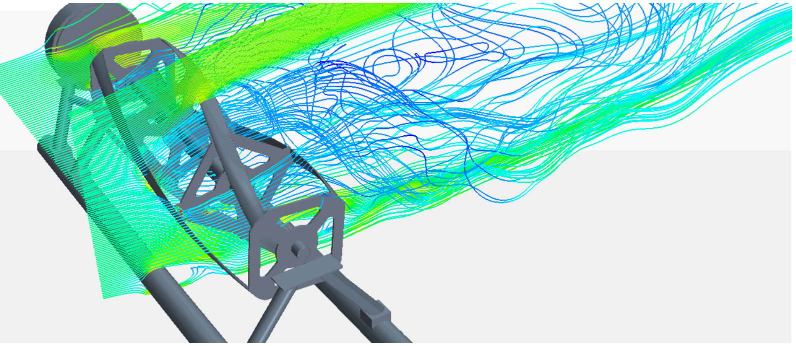
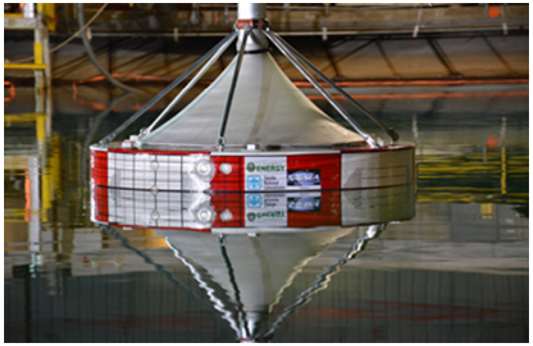




Renewable Energy Levelized Energy Cost Modeling:

Lessons for Marine Energy Conversion Technologies

Peter H. Kobos, Vincent S. Neary, Bernadette A. Hernandez-Sanchez and Ryan G. Coe (Water Power)
Brian Naughton, Josh Paquette and Brandon Ennis (Wind)
Joseph Ulibarri (Water and Wind)
Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline*

- **Marine Hydrokinetics Technology**
- **Capital Expenditures (CAPEX) and Operational Expenditures (OPEX)**
- **Lesson from other renewables**
- **Approaches to Increase Performance, Assess the Resource and Reduce Costs**
  - **Advanced Controls**
  - **Advanced Materials**
  - **Device Performance Modeling**
  - **Other areas**
- **Concluding remarks**

* Select presentation materials adapted from Neary et al., 2016.

Water Power Technologies

The Water Power Technologies program conducts applied research to improve the performance and reliability of marine hydrokinetic (MHK) technologies while lowering the cost of energy.

History & Impact

- Began in 2009 out of DOE Offshore Wind
- Supports ~25 researchers and collaborative capabilities in 9 Sandia organizations.
- Increased power absorption by ~200% using Advanced Dynamics and Controls for experimental Wave Energy Converter (WEC)
- Developed software for performance and costs, Adapted by industry & universities.
- Wave Energy Prize - Supported winning teams.
- U.S. Water Power could power 81 Million new homes; Up to ~700,000 new jobs[1].

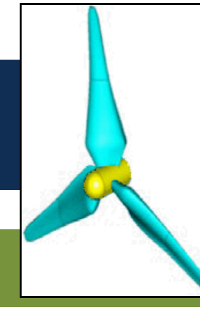
Technical Strategy

- Leverage expertise in Advanced Controls, Materials Research, Device Performance Software and High-Fidelity Modeling.
- Leverage Sandia capabilities across departments, partner with industry & universities.

1. DOE, 2017, *Future Outlook,* Traditional Hydropower and MHK.

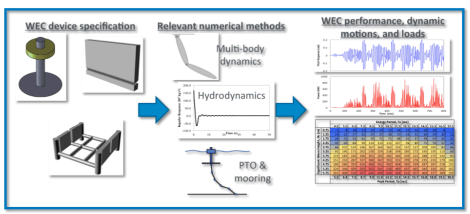
Water Power Technologies

The Water Power Technologies program conducts applied research to improve the performance and reliability of marine hydrokinetic (MHK) technologies while lowering the cost of energy.

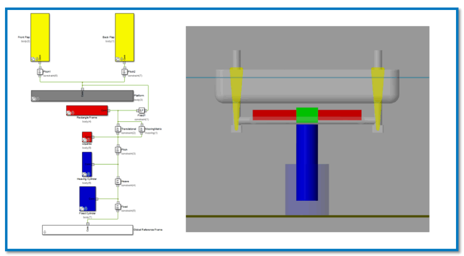


Opportunities

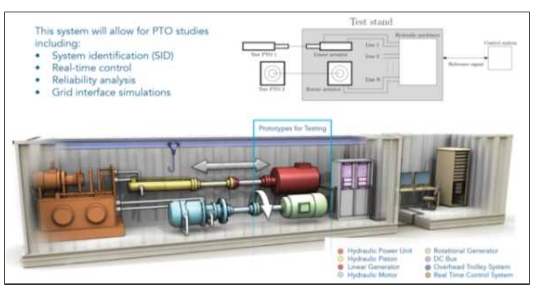
- Testing/collaboration at DOD Maneuvering And Sea Keeping (MASK) basin in Bethesda, MD.
- Developing new power take-off test stand.
- 6 Staff members work with 5 industry partners, 6 universities – joint funding opportunities.
- Evolving device design standardization: Engaging with international standards committees & on industry technical projects.



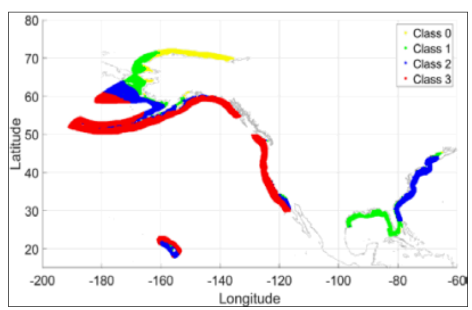
WEC-Sim Workflow



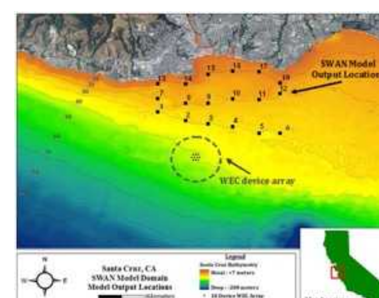
WEC-Sim Model of FOSWEC



Sandia Water Power Takeoff Laboratory (SWEPT)



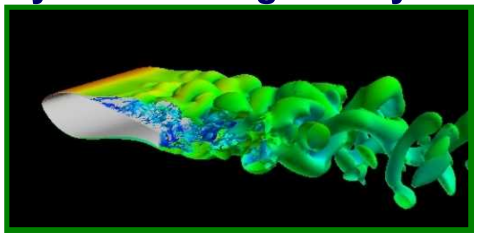
Resource Assessment



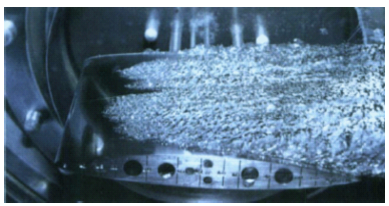
Potential Siting Assessments

MHK Research Focus Areas at Sandia National Labs

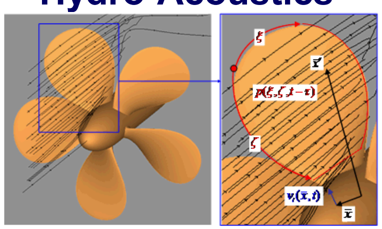
Hydrofoil Design/Analysis



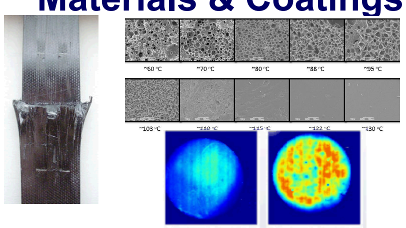
Cavitation



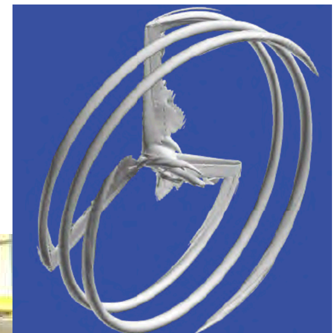
Hydro-Acoustics



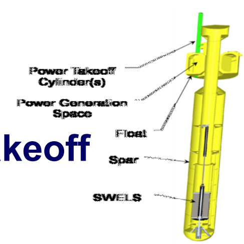
Materials & Coatings



Performance Modeling

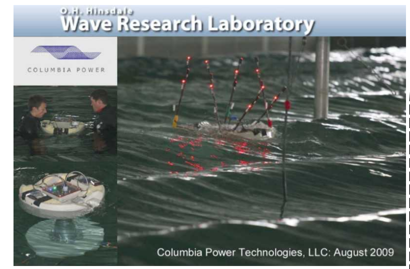


Rotor Design & Testing



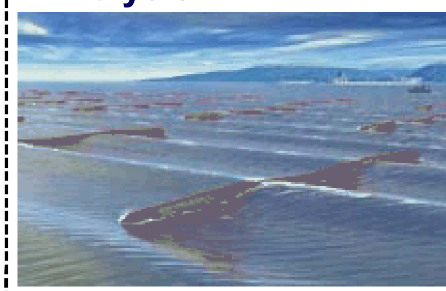
Power Takeoff Testing

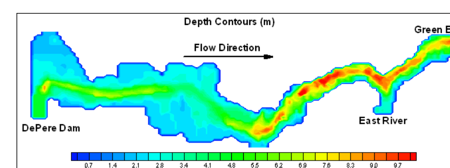
Columbia Power 1/15th Scale Test (OSU)



Water Tunnel (PSU/ARL)

Coupled Device Array and Environmental Analysis





SNL EFDC

Technology Development Cycle

Components | Sub-systems | System Testing | Deployment

LCOE Formula: Approaches to Lower the Costs

Focus on Materials Selection and Research + Best Practices to Reduce Costs

$$LCOE = \frac{(FCR \times CapEx) + OpEx}{AEP}$$

Focus on Component / System Performance Increases

LCOE = Levelized Cost of Energy
AEP = Annual Energy Production
CapEx = Capital Expenditures[1]
OpEx = Operations and Maintenance Expenditures[2]

Does the Traditional LCOE approach capture all the value for Water Power or other Renewables?

1 For Wave Energy Converters, this may include Development costs, Infrastructure, Mooring/Foundation, Device Structural Components, Power Take Off (PTO), Subsystem Integration, Installation, installation, and possibly profit and contingency costs. 2 This may include Marine Operations & Maintenance (O&M), Shore-side Operations & Maintenance (O&M), Post Installation, Environmental O&M, Replacement Parts, Consumables, and possibly Insurance.

LCOE Formula (CapEx Categories)

- Development
- Infrastructure
- Mooring/Foundation
- Device Structural Components
- Power Take Off (PTO)
- Subsystem Integration & Profit Margin
- Installation
- Contingency

$$\text{LCOE} = \frac{(\text{FCR} \times \text{CapEx}) + \text{OpEx}}{\text{AEP}}$$

LCOE Formula (OpEx Categories)

- Marine Operations & Maintenance (O&M)
- Shore-side Operations & Maintenance (O&M)
- Post Installation Environmental O&M
- Replacement Parts
- Consumables
- Insurance

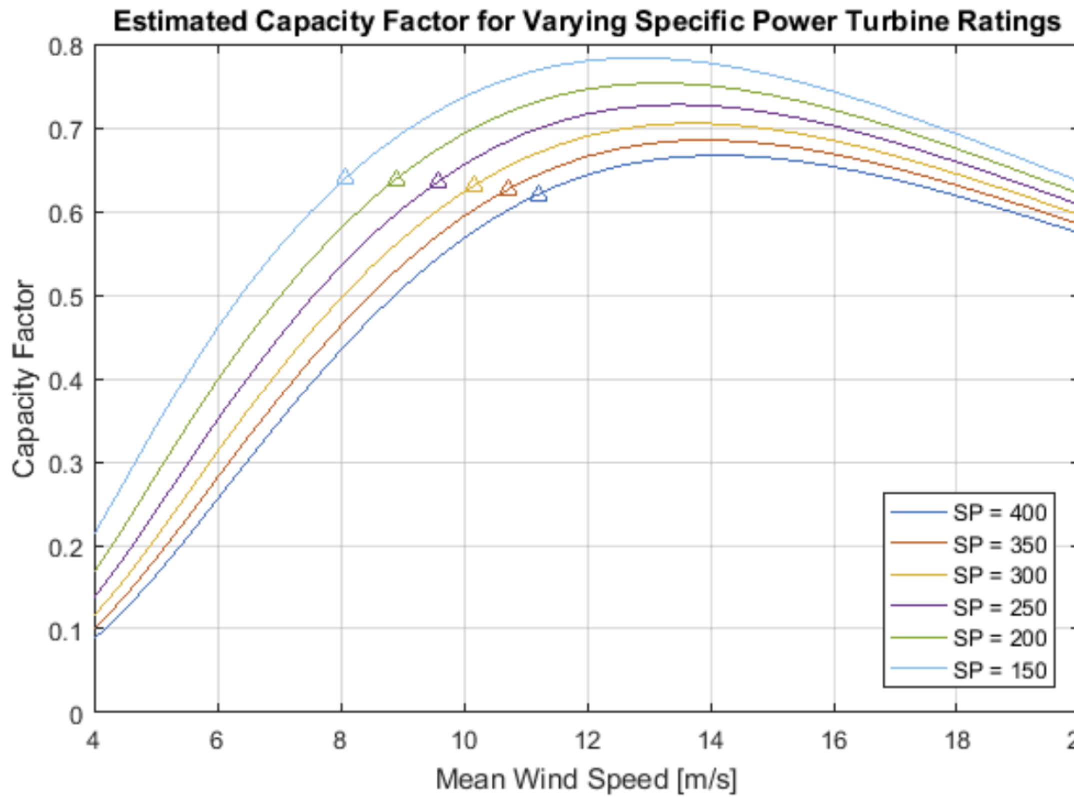
$$\mathrm{LCOE} = \frac{(\mathrm{FCR} \times \mathrm{CapEx}) + \mathrm{OpEx}}{\mathrm{AEP}}$$

Lessons from Other Renewables: Wind Power

- Mature industry – Predominantly a 3-Blade Design
- Optimizing systems for LCOE–not always for component performance

EXAMPLE:
Increasing the wind rotor size to capture more energy

- Wind turbine capacity factor is inherently higher for low specific power designs due to:
  - Increased energy capture at the same wind speed
  - Reduction in the turbine's rated wind speed
- At 6 m/s, the energy production is over 80% higher for a specific power design of 150 versus 400 W/m2
- Can increase the energy capture while maintaining constant system loads



The proposed blades reach unprecedented lengths

Lessons from Other Renewables: Wind Power

- Economies of Scale can reduce OpEx
  - Wind farms → Wave Energy Converter Farms
  - Leverage & minimize visits for operations and maintenance
  - Design choice: Extreme load survival (3 blade, upwind)
- Co-location may reduce LCOE
  - Offshore wind combined with Marine Hydrokinetic (MHK) devices
    - Cycles of wind and waves may be off → potentially manage the loads on the wind towers by extracting the wave energy
- MHK industry still growing
  - Fundamental R&D still ongoing, lower TRL levels in many areas
  - Too early for Learning (Experience) Curve cost-reducing effects?

PV Module Experience Curve example

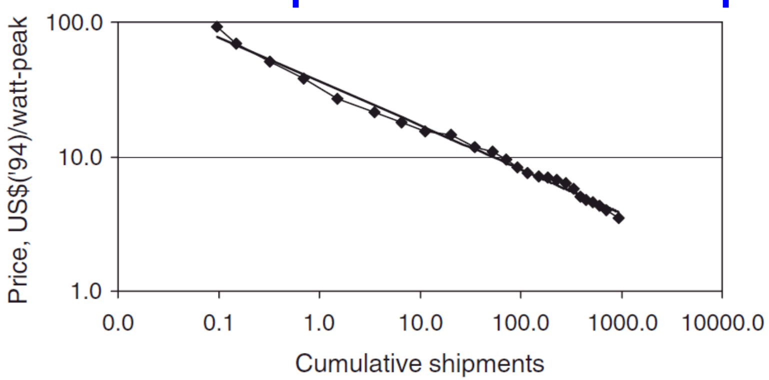
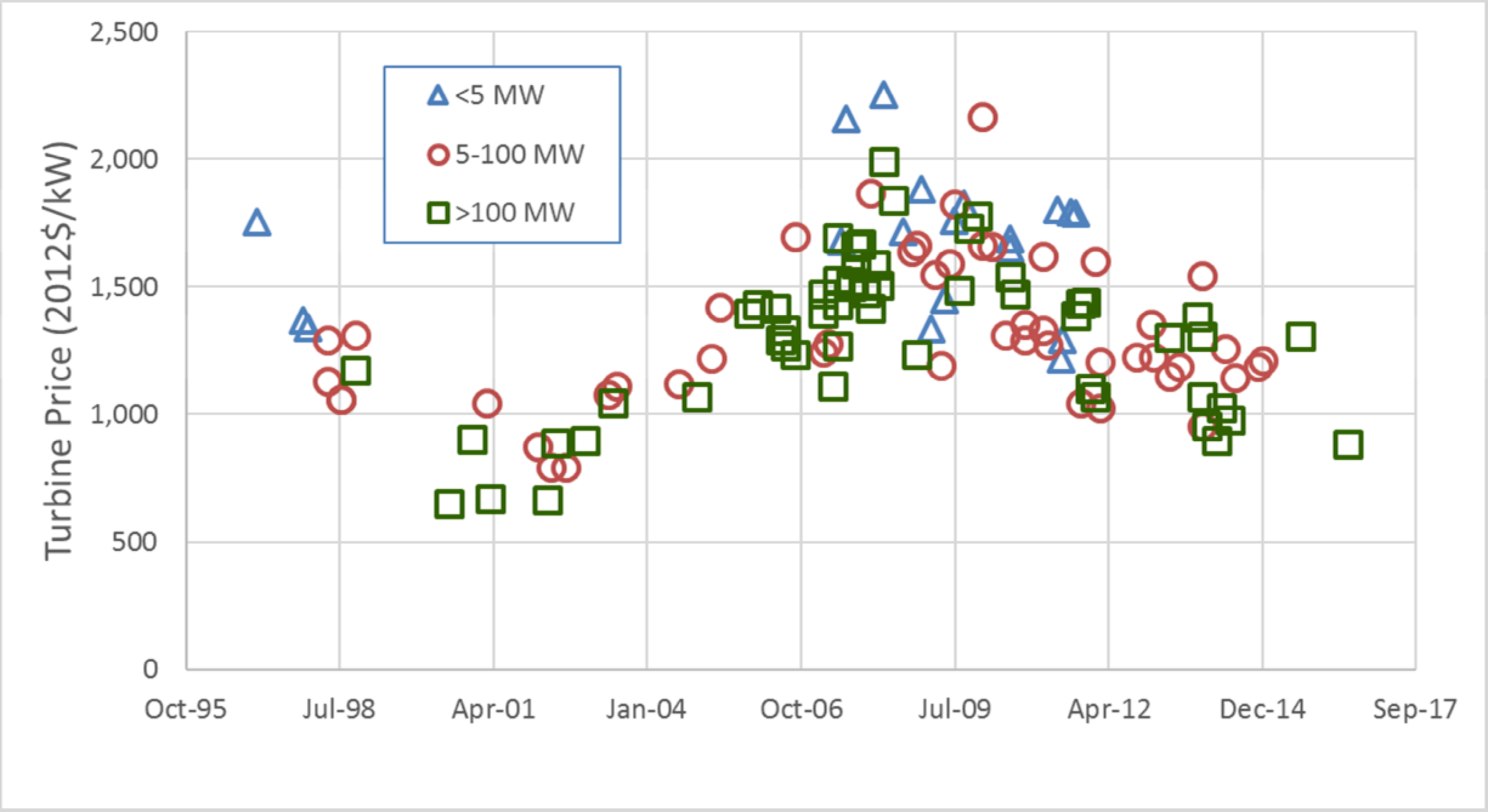


Fig. 7. An experience curve for PV modules (adapted from Harmon, 2000).
(Kobos et al., 2006)

Lessons from Other Renewables: Wind

- Commodity Costs affected Wind ~2009
  - e.g., Steel prices increased – tower costs represent ~50% of CapEx costs
- Turbine Upscaling



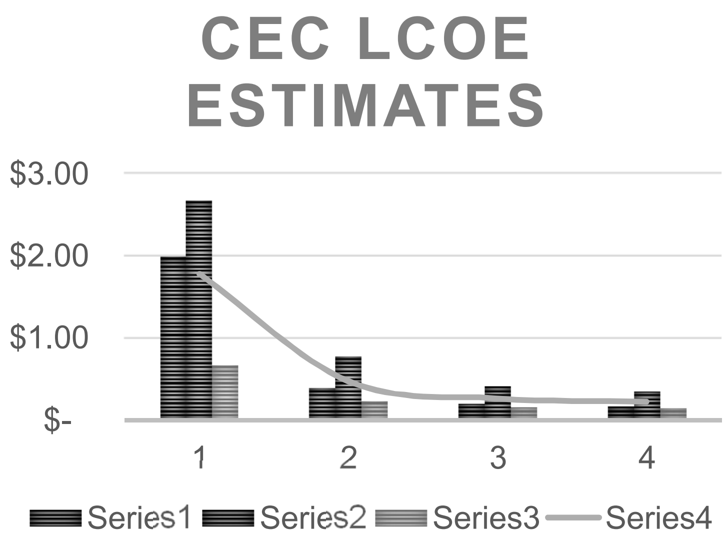
Adapted from Wiser, 2013, Wiser et al., 2016. (https://energy.gov/eere/wind/downloads/2016-wind-technologies-market-report)

MHK LCOE insights

Current Energy Converters

- Literature: 30-60 ¢/kWh
- Reference Model Insights:

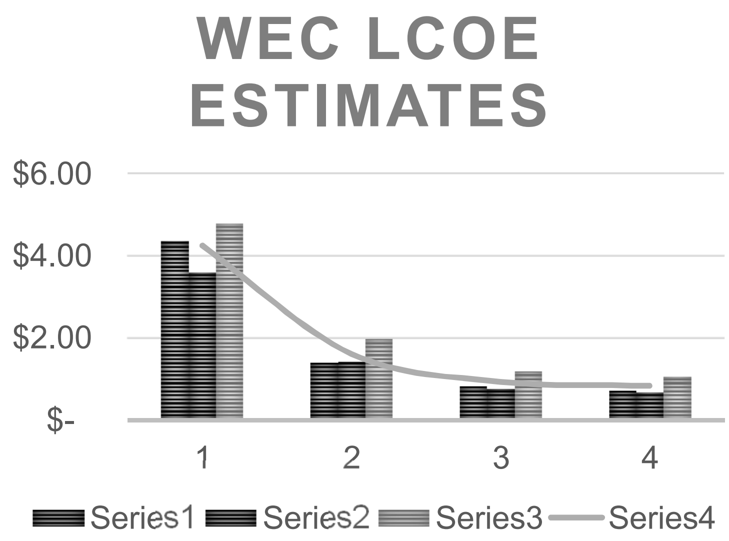
	1-unit	10-unit	50-unit	100-unit
RM1	$ 1.99	$ 0.40	$ 0.20	$ 0.17
RM2	$ 2.67	$ 0.78	$ 0.42	$ 0.35
RM4	$ 0.67	$ 0.24	$ 0.17	$ 0.15
average	$ 1.78	$ 0.47	$ 0.26	$ 0.22



Wave Energy Converters

- Literature: 30-100 ¢/kWh
- Reference Model Insights:

	1	10	50	100
RM3	$ 4.36	$ 1.41	$ 0.83	$ 0.73
RM5	$ 3.59	$ 1.44	$ 0.77	$ 0.69
RM6	$ 4.79	$ 1.98	$ 1.20	$ 1.06
average	$ 4.25	$ 1.61	$ 0.93	$ 0.83



$/kWh

Device Performance Modeling: Reference Models

Developed 6 public domain designs to obtain baseline performance and Cost of Energy (COE) estimates

Incorporated:

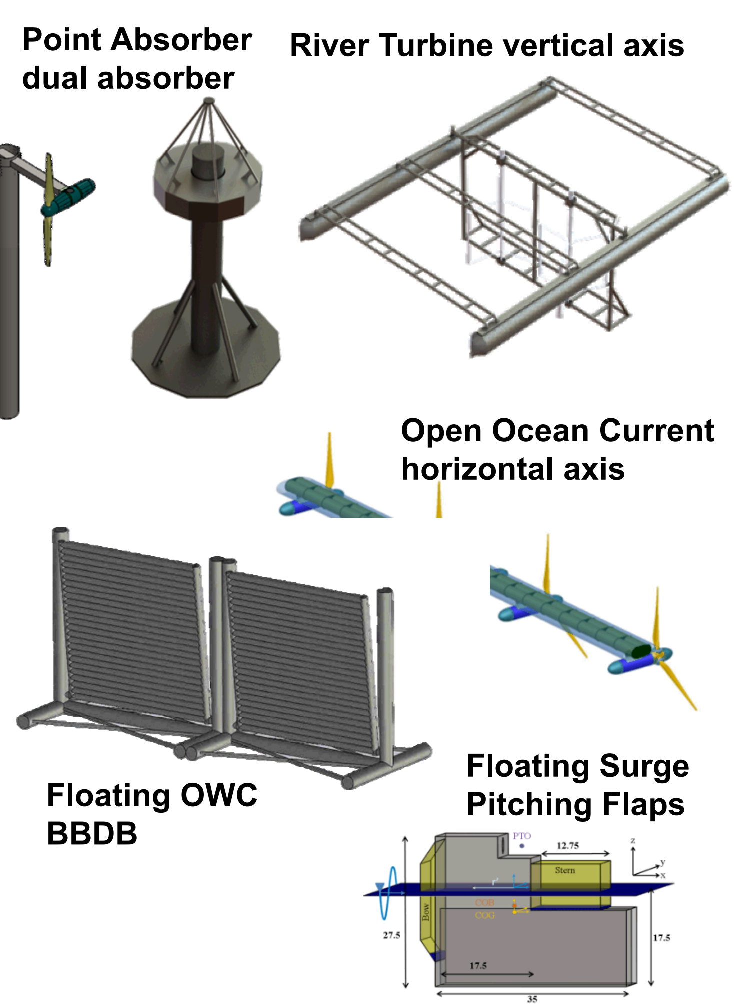
- Power performance models
- Structural models
- Anchor and Mooring Design
- Economic Model
- PTO Design
- O&M / Installation
- Permitting & Environment

Project Impact:

- All reference models are public domain serving broader stakeh needs
- Process of obtaining COE facilitates knowledge / modeling tool gaps that the industry is facing thus allowing DOE to target their researc dollars effectively
- The creation of independent and experimentally verified COE acro multiple device architectures legitimizes the comparison

Information Dissemination:

- Project reports, Reference model designs
- Data from scaled model studies, COE model spreadsheets
- Release of RM5 and RM6 information

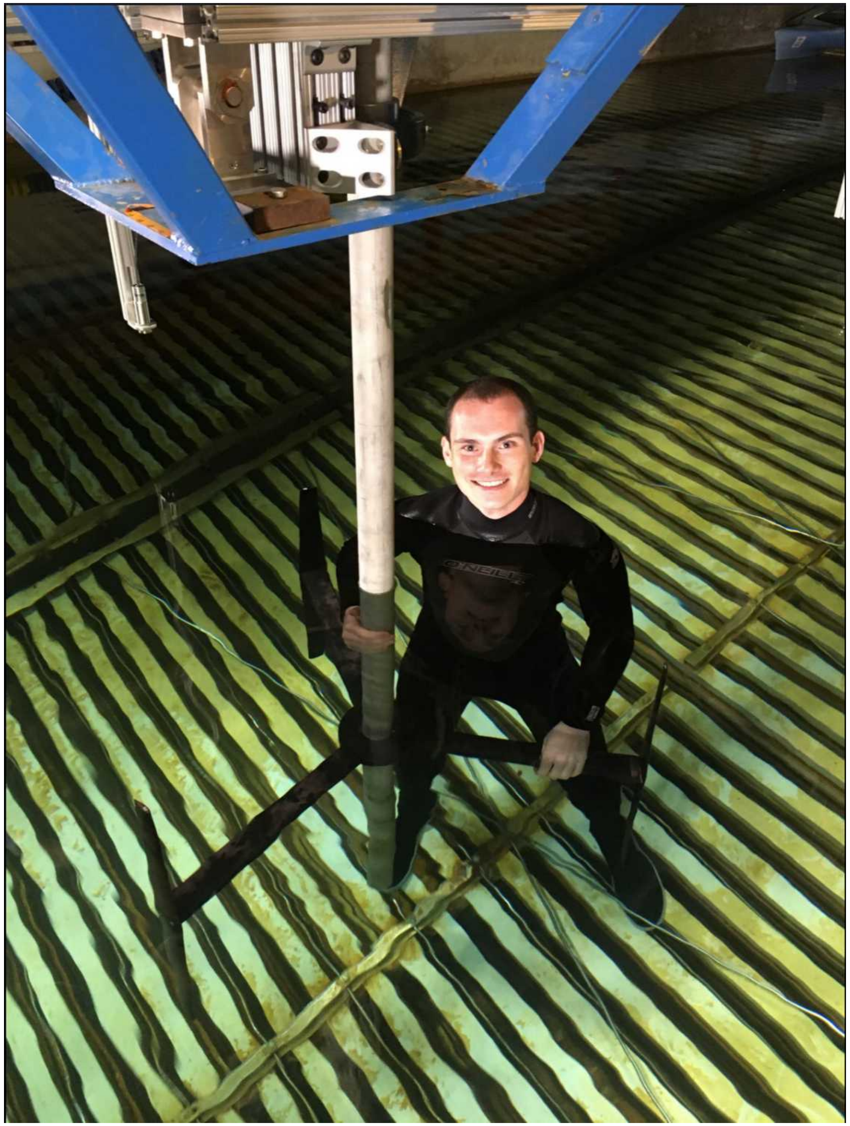


Using Reference Models

RM2: River Current Turbine

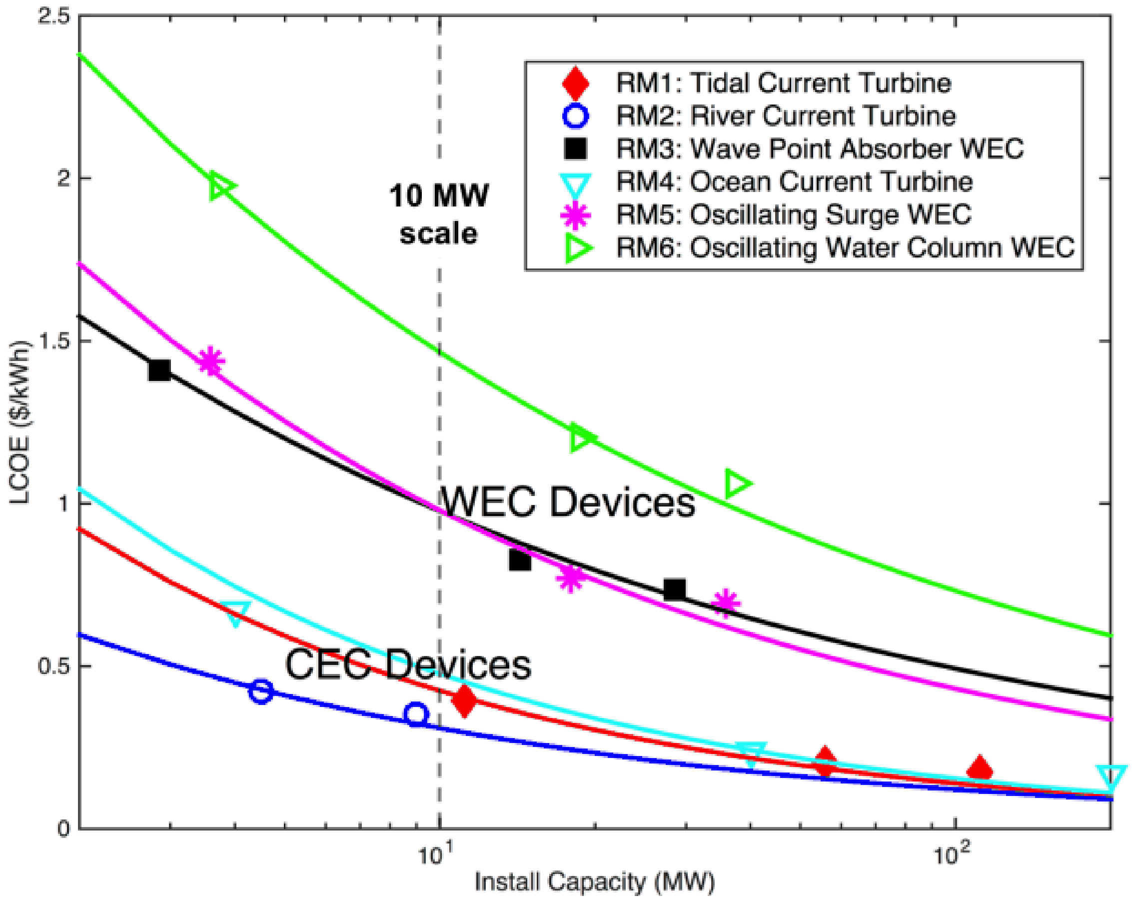
Photo: crossflow turbine testing at the Naval Academy tow tank

Tested: Turbine tested at multiple labs, the University of Minnesota & the University of New Hampshire.



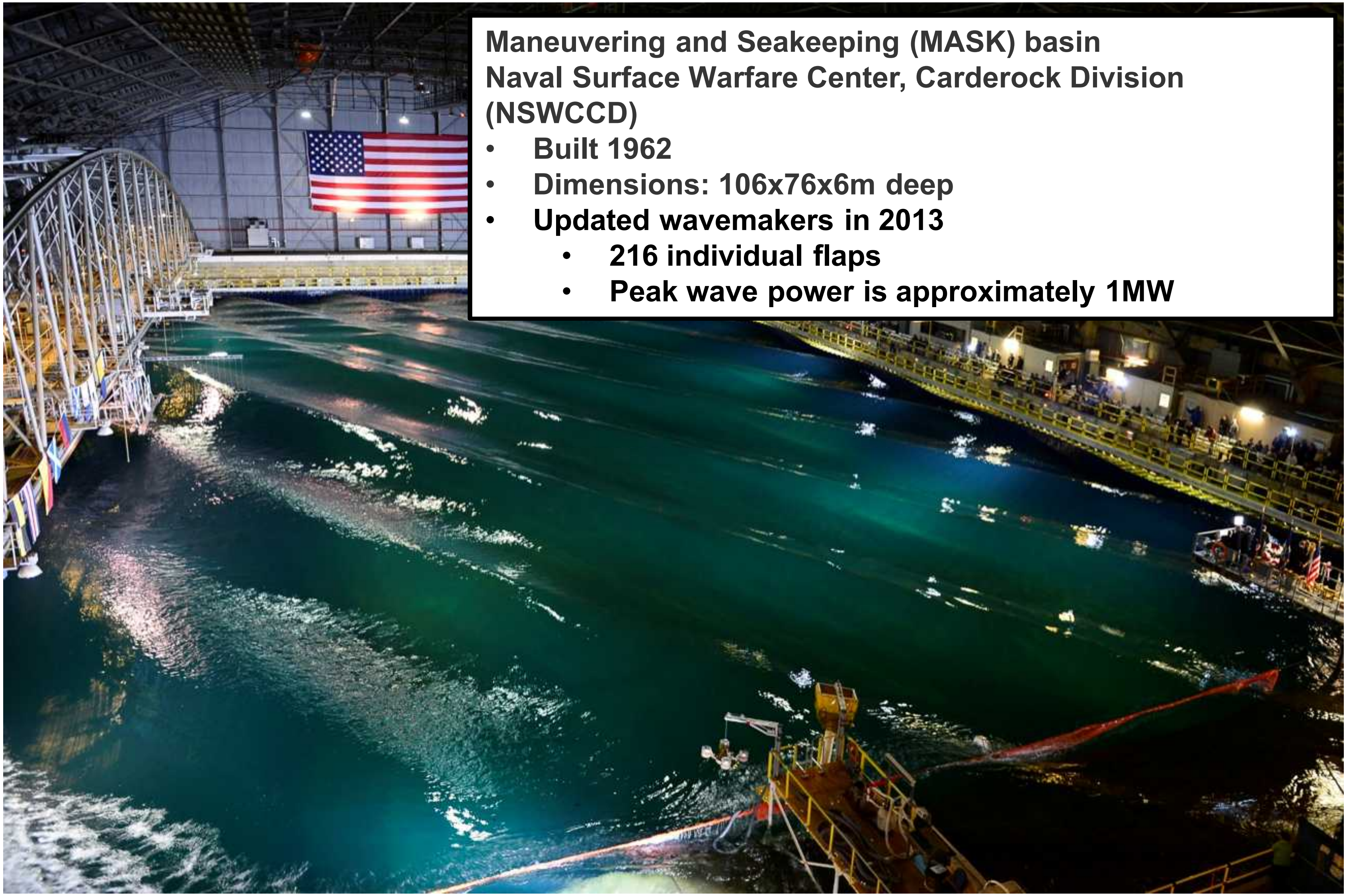
Reference Model Results/Estimates: 10 MW Installed Capacity

- CECs
  - ≈ $0.31-0.45/kWh
  - Varying resource conditions impact installation, permitting, capacity factors, etc.
- WECs
  - ≈ $0.98-1.53/kWh
  - At 10 MW structural mass is the largest contributor to LCOE.



Technology Build out will help verify Cost reductions

Increasing Performance: Test Wave Energy Converter Hardware & Controls



Maneuvering and Seakeeping (MASK) basin
Naval Surface Warfare Center, Carderock Division (NSWCCD)

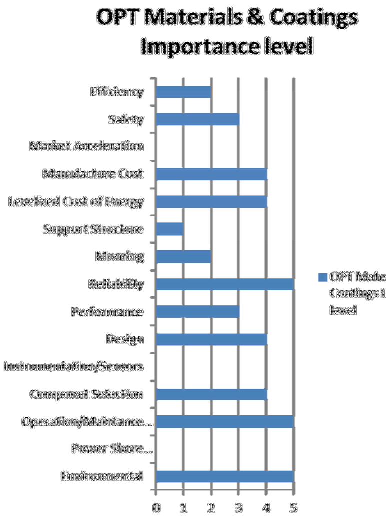
- **Built 1962**
- **Dimensions: 106x76x6m deep**
- **Updated wavemakers in 2013**
  - **216 individual flaps**
  - **Peak wave power is approximately 1MW**

Advanced Dynamics and Controls: Doubled the Power Output

https://www.youtube.com/watch?v=XCB12Het4c4&feature=youtu.be

MHK Advanced Materials & Coatings

MHK Industrial Review

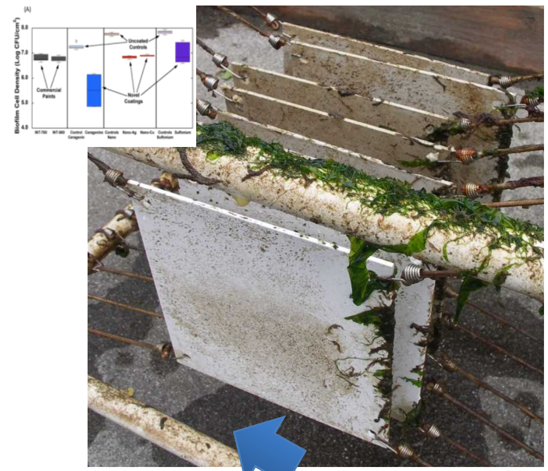


Water Power Materials Science & Engineering

PNNL Marine Science Laboratory

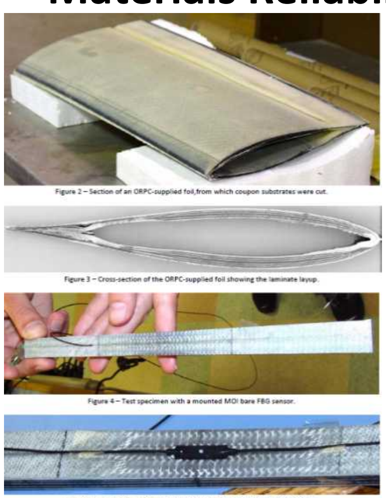
Pacific Northwest NATIONAL LABORATORY

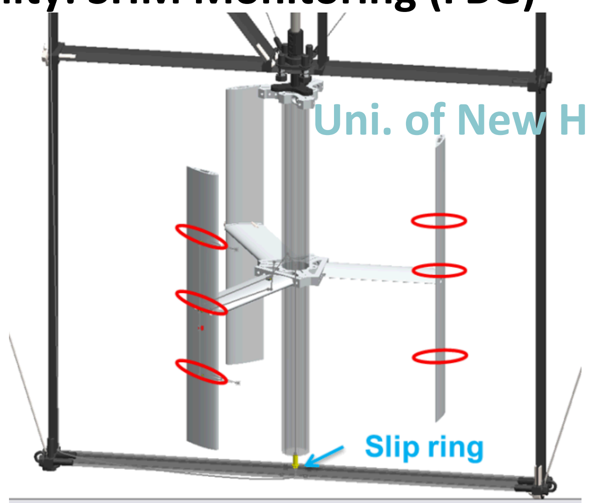
Protective Coatings



PNNL Open Water Testing

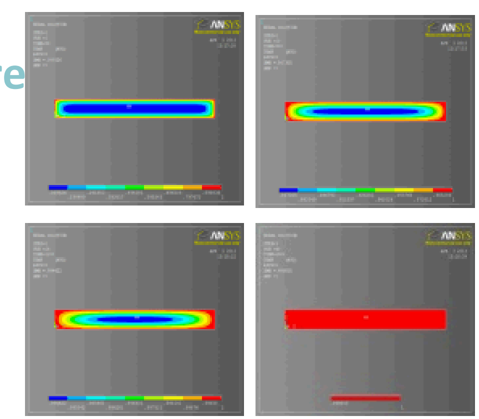
Materials Reliability: SHM Monitoring (FBG)

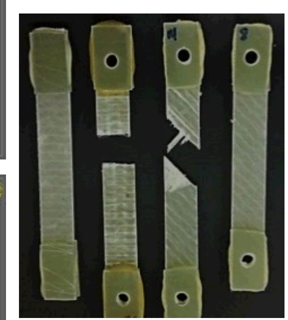




Uni. of New Hampshire

MHK Composite Performance

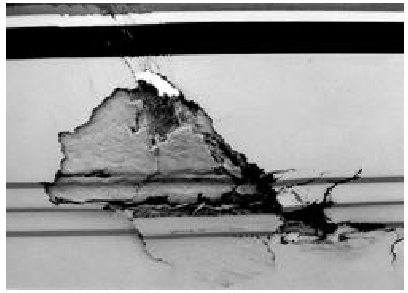




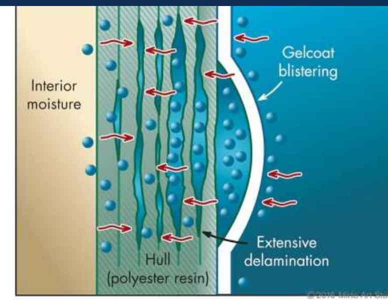
Materials Research

Engineering designs of MHK devices have difficult, although not unique, materials challenges

lightweight yet stiff



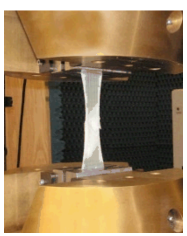
Strong & durable



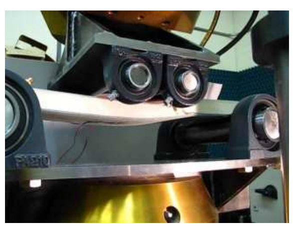
resist environmental degradation

inexpensive & easy to integrate into manufacturing

- Specialized applications require this level of materials application, knowledge and sophistication
- Challenges require broad experience to understand all of these challenges
- Our Technical Approach is to help bridge the technology gaps and knowledge that span across all four of these materials challenges through….

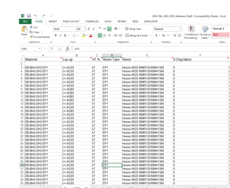


Coupons to Structural elements



Elements to Substructure

Testing to Dissemination (host database)



- **Hosted Workshop to Identify Composite Related Barriers** – What are the composite materials related manufacturing science and engineering barriers that increase the costs?

Device Performance Modeling: WEC-Sim

SNL (Kelley Ruehl) & NREL collaboration

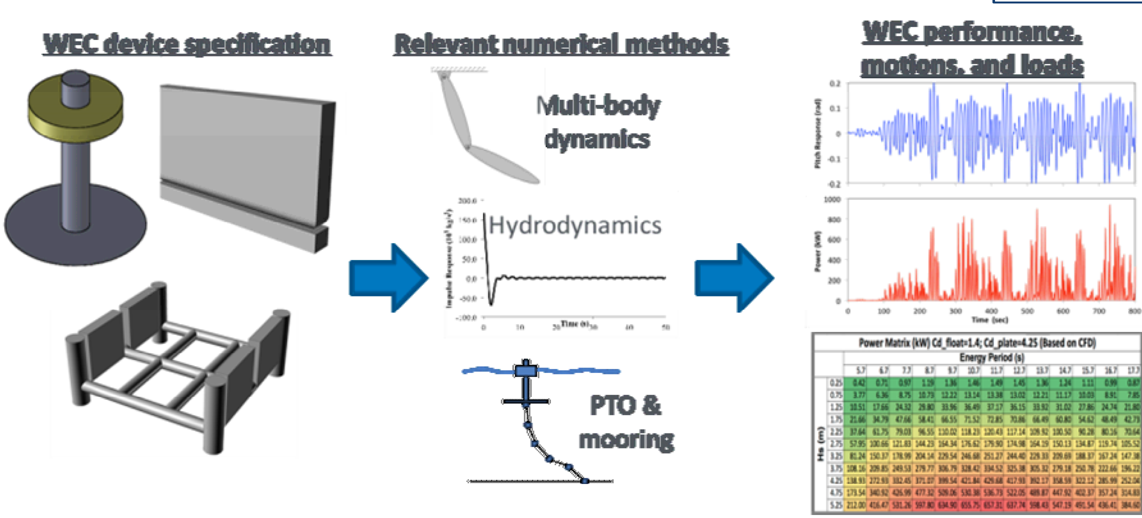
Used by the WEC community to simulate WEC dynamics and reduce WEC design uncertainty and improve power performance

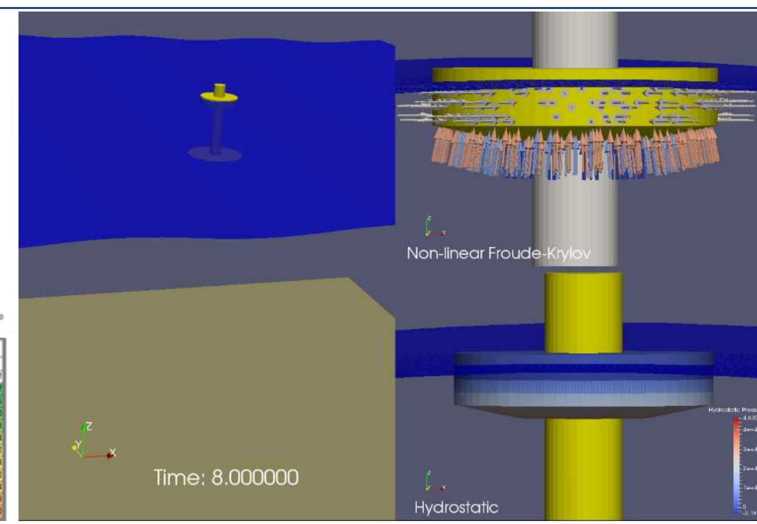
Wave Energy Converter Simulator

- Developed in MATLAB/Simulink using the multi-body dynamics solver SimMechanics
- Models devices comprised of rigid bodies, power-take-off systems, and mooring systems
- Performs time-domain simulations in 6 degrees-of-freedom
- Download it on GitHub: https://github.com/WEC-Sim/WEC-Sim

- Helped Wave Energy Prize contestants (5/9 finalists)
- Large-scale adoption by industry / academia / researchers domestically and internationally, notably:

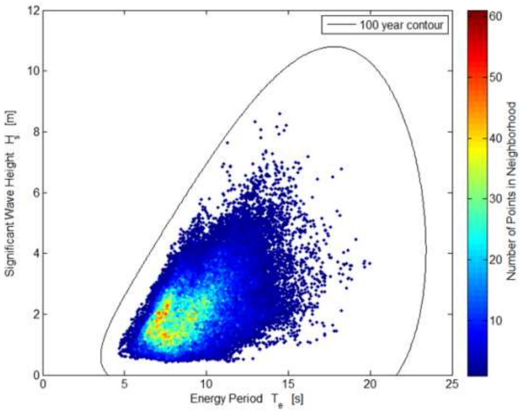
The University of Maine
Wave Energy Prize, U.S. Department of Energy
AquaHarmonics
Harvest Wave Energy
NWEI northwest energy innovations
Oscilla Power
OPT Ocean Power Technologies
OSU Oregon State University
Ecomerit Technologies
wave energy Scotland
cruz atcheson consulting engineers
University of Hawai'i Mānoa
Virginia Tech
The University of Texas at Austin
Maine Marine Composites

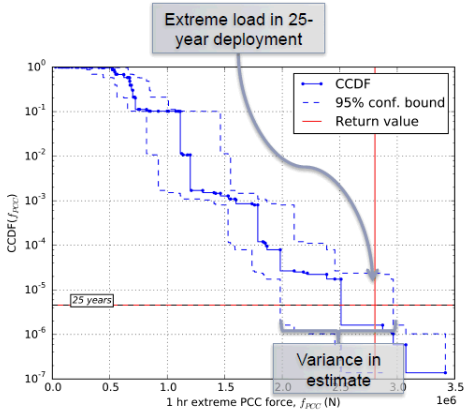


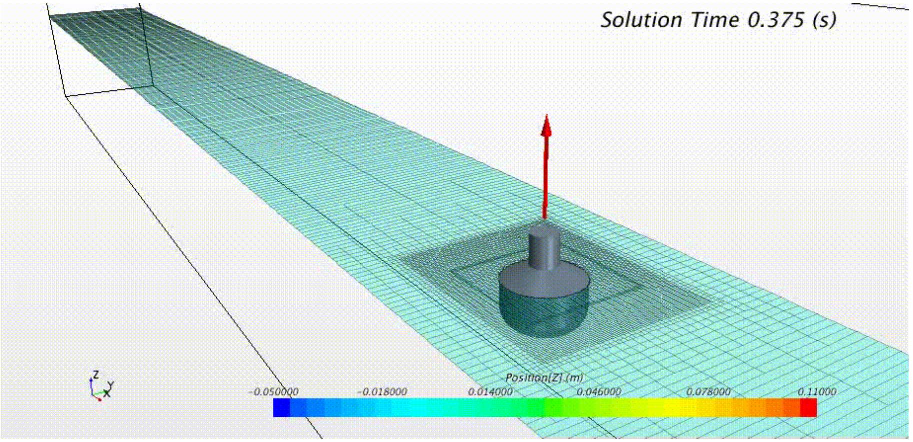


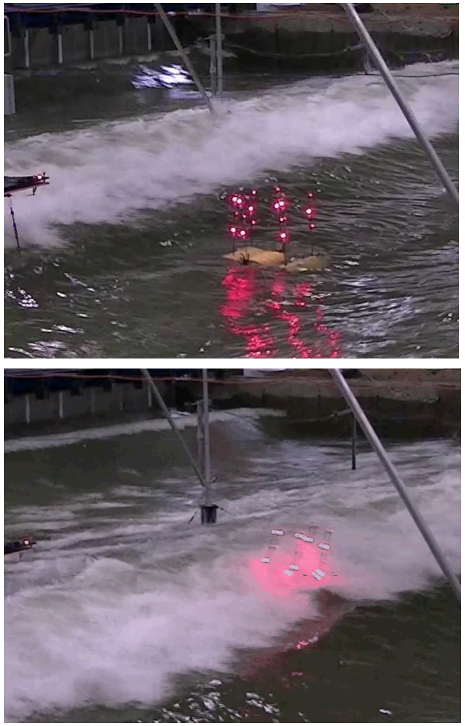
Device Performance Modeling

WECs must be designed to respond to ocean waves: Probabilistic methods for predicting extreme design loads → Improve best-practices for design response analysis of WECs









Images courtesy of Columbia Power

Concluding Remarks

→ **LCOE**

- Can Reduce by:
  - Focus on Materials Selection & Research + Best Practices (CapEX)
  - Focus on increasing Annual Energy Output (increasing performance)
  - Including the System's Costs and Value-added benefits
- CED Cost drivers: Power Takeoff, Structure, O&M
- WEC Cost drivers: Structure, Mooring, O&M

→ **Advanced Controls, Materials Research, Systems Performance Modeling**

- Systems may increase power production substantially; provide longevity & cost reductions; increase performance, avoid challenges

→ **Learn** from the past experiences of other Renewable Energy Technologies that are closer/in the market today

THANK YOU

Acknowledgements

- The authors would like to thank the Department of Energy, office of Energy, Efficiency & Renewable Energy for supporting this research, as well as colleagues at Sandia National Laboratories, others at the National Renewable Energy Laboratory, other national laboratories and in the Marine Hydrokinetic research and industrial community.
- Presentation elements adapted from Neary et al., 2016.
- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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