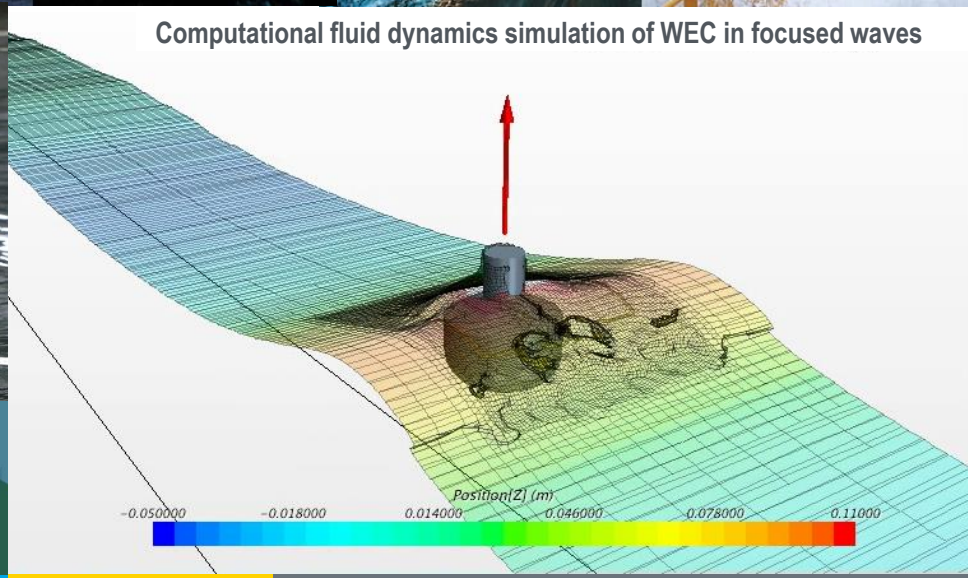
Water Power Technologies Office Peer Review
Marine and Hydrokinetics Program

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

FOSWEC wave tank testing and WEC-Sim simulation



Computational fluid dynamics simulation of WEC in focused waves

Wave Energy Converter Modeling

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Project Overview

Wave Energy Converter (WEC) Modeling:
Empower the advancement of WEC technologies by enabling the efficient, accurate prediction of power performance and extreme loading to inform structural design and risk reduction through the development and validation of a suite of open-source design and analysis tools (**WEC-Sim**), open-access validation datasets, and an extreme condition modeling (**ECM**) framework and toolbox.

The Challenge: WECs are typically made up of multiple bodies and are designed to maximize their relative motion at dominant sea states (as resonant devices), resulting in complex nonlinear hydrodynamics, particularly during extreme sea states.

- Uncertainty in predicting WEC performance is increasing the uncertainty for WEC design optimization and wave energy cost estimation.
- Uncertainty in designing WEC devices to survive extreme conditions is slowing the pace of technology development and increasing the investment risk.

Partnership

- National Renewable Energy Laboratory (NREL) (PI: Yi-Hsiang Yu)
- Sandia National Laboratories (SNL) (PI: Kelley Ruehl; CO-PI: Ryan Coe)

Program Strategic Priorities

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Technology Maturity

- **Test and demonstrate prototypes**
- Develop cost-effective approaches for installation, grid integration, operations and maintenance
- Conduct R&D for innovative MHK systems and components
- **Develop tools to optimize device and array performance and reliability**
- Develop and apply quantitative metrics to advance MHK technologies

Deployment Barriers

- Identify potential improvements to regulatory processes and requirements
- Support research focused on retiring or mitigating environmental risks and reducing costs
- Build awareness of MHK technologies
- Ensure MHK interests are considered in coastal and marine planning processes
- Evaluate deployment infrastructure needs and possible approaches to bridge gaps

Market Development

- Support project demonstrations to reduce risk and build investor confidence
- Assess and communicate potential MHK market opportunities, including off-grid and non-electric
- Inform incentives and policy measures
- Develop, maintain, and communicate our national strategy
- Support development of standards
- Expand MHK technical and research community

Crosscutting Approaches

- Enable access to testing facilities that help accelerate the pace of technology development
- Improve resource characterization to optimize technologies, reduce deployment risks, and identify promising markets
- Exchange of data information and expertise

Project Strategic Alignment

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Technology Maturity

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The Impact

- Provide the WEC industry with a set of customizable open-source WEC performance and extreme loading analysis tools/datasets to:
  - Reduce WEC design uncertainty, improve power performance, and improve survivability in extreme conditions
  - Accelerate pace of WEC technology development with reduced investment risk
- The final products are validated, open-source, WEC simulation tools, open-access validation datasets, and documentation. Products can be used and customized to meet industry needs.

Technical Approach

Develop a set of open-source tools that are validated and customizable to meet users' needs, used to analyze WEC power performance, and predict the extreme loading on the system under critical wave environments

- **WEC-Sim code development:** Simulate WEC devices comprising rigid bodies (multi-body dynamics), power-take-off systems (PTO-Sim), and mooring systems (MoorDyn)
- **WEC-Sim validation testing:** Perform wave tank test and develop an open-access validation dataset
- **ECM workshop and technical meeting:** Exchange experience with the WEC community, understand current challenges, and investigate potential pathways to solve the challenges
- **ECM framework and WEC Design Response Toolbox (WDRT) development:** Include relevant toolsets and numerical strategies to more accurately and efficiently evaluate system design loads
- **Dissemination and community support:** Lead public training courses and webinars, and manage online Q&A forums to assist the WEC community's utilization of models and methodologies
- **Industry support projects:** Work with industry developers to improve their devices' power performance and survivability by implementing WEC-Sim, the ECM Framework ,and the WDRT

Accomplishments and Progress (WEC-Sim)

WEC-Sim development and release (v1.0 in 2014; v2.1 in 2016)

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

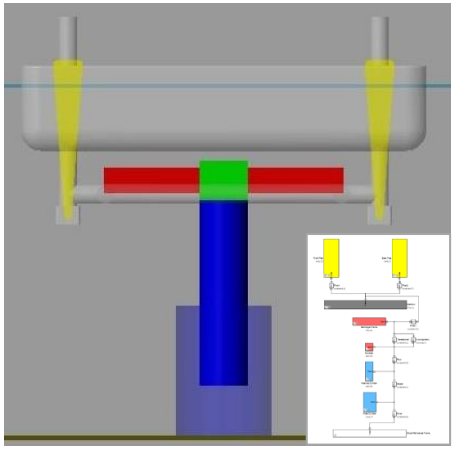
- Helped Wave Energy Prize contestants (5/9 of the finalists) to analyze and improve their designs during the competition
- Large-scale adoption by industry/academia/researchers domestically and internationally, notably:

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

Award:

Won the 2015 International Conference on Ocean, Offshore and Arctic Engineering (OMAE) Center for Ocean Energy Research Competition (COER), established the team as the world leading modeling expert in the field

WEC-Sim numerical model of the experimental testing

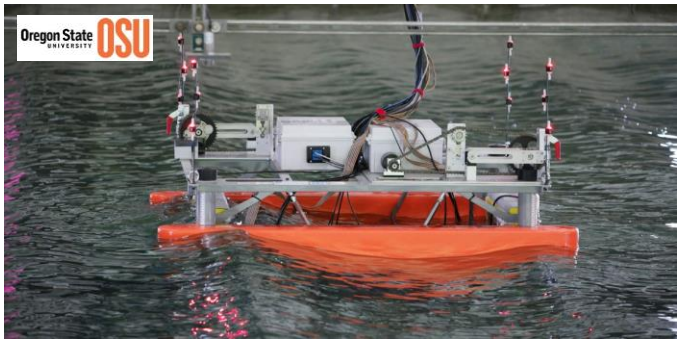


WEC-Sim win at OMAE COER coding competition

Accomplishments and Progress (WEC-Sim)

Completed WEC-Sim validation wave tank testing

- An open-access validation dataset was developed and is available via the Marine and Hydrokinetic Data Repository
- The multi-body WEC testing experience was invaluable and will help reduce technical barriers for WEC developers during future wave tank testing



WEC-Sim experimental testing at Hinsdale Wave Research Lab

Participating/leading the International Energy Agency Ocean Energy Systems Task 10

- This task on WEC modeling verification and validation will internationally assess the accuracy and establish confidence in the use of numerical models for WECs.

OES OCEAN ENERGY SYSTEMS

WEC-Sim training courses/webinars:

- Four training courses were held at the 2015 International Network on Offshore Renewable Energy Symposium, Oregon State University, 2016 Marine Energy Technology Symposium, and the University of Maine targeted at engaging and growing WEC-Sim user-community
- Providing hands-on demonstrations accelerated the learning curve and increased understanding of the needs directly from community to incorporate them in the code developmentt

Accomplishments and Progress (ECM)

The ECM workshop (Albuquerque, New Mexico in 2014)

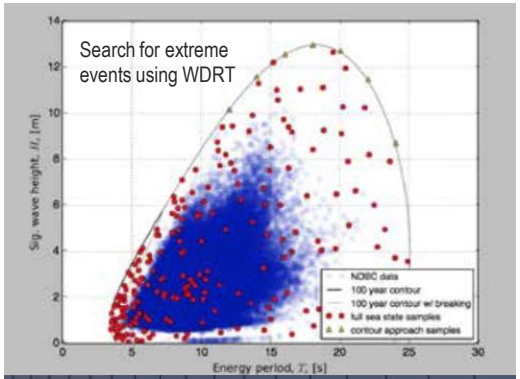
The ECM workshop was held to review the current state of knowledge on numerical and physical ECM for WECs, including knowledge leveraged from other floating and offshore systems, and investigation in to how these methodologies could be improved.

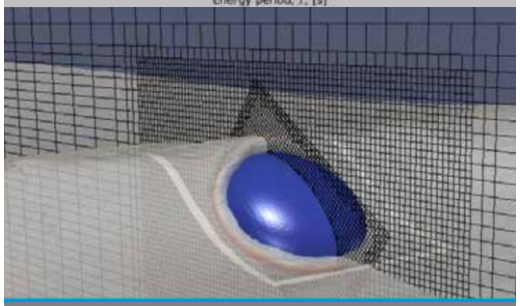
ECM Framework and WEC WDRT:

- An efficient and risk-based numerical strategy for predicting system design load and a set of tools for environmental characterization, extreme response statistics, fatigue, and equivalent design wave analysis were developed
- The framework and toolbox helps to reduce WEC design uncertainty and thereby minimize the investment risk

Industry Support Tasks

- Worked with M3 Wave to identify the cause, and investigate possible solutions for, scouring underneath and surrounding the M3 Wave device and thereby improve the system's performance and reliability
- Working presently with Oscilla Power and Ecomerit to analyze their WEC's system design loads





Computational fluid dynamics simulations of a WEC in focused waves

Project Plan and Schedule

Project Initiation and Completion Dates

- WEC-Sim development began in FY13 and will end at the end of FY17
- The ECM project began in Q2 FY14 and will end at the end of FY17
- Industry FOA support (presented as part of ECM) began in FY16 and will end in FY17

Delayed and Slipped Milestones

- **FY15 Q3 ECM**: CFD simulations for the DNV-GL proposed NUWAVE computational fluid dynamics (CFD) benchmarking project were canceled due to project suspension by DNV-GL
- **FY15 Q3 WEC-Sim**: The first phase of the validation wave tank testing was delayed due to contracting issues, and was completed in Q1 FY16
- **FY16 Q4 WEC-Sim:** The release of the validation wave tank testing data through the MHK-DR was delayed due to support for the Wave Energy Prize project, and completed in Q1 FY17

Go/No-Go Decisions

- **FY15 Q3 WEC-Sim**: The WEC-Sim team advised against moving WEC-Sim away from a MATLAB platform to a fully open-source platform. Instead, it was recommended that future efforts focus on reviewing and adapting numerical modeling methods for novel types of WEC device.
- **FY15 Q3 ECM**: The ECM team recommended against an ECM testing campaign in FY16
- **FY16 Q3 ECM**: Based on a meeting with DOE HQ, an ECM research plan for FY17 has been outlined

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-Share	DOE	Cost-Share	DOE	Cost-Share
$1,725k	$0	$2,338k	$0	$2,314k	$0

Budget Notes

- FY16: $100k was transferred from another project as carryover, but is included here as BA as it is new funding to the project.

Project Spending

- 82% of current project budget has been expended.
- The budget was split ~50/50 between NREL and Sandia.
- The budget includes $500k for industry-support projects (Funding Opportunity Announcements [FOAs])
- These costs include the expense of numerical model development, wave tank testing, high-performance CFD simulation models, and hosting workshops and training classes

Research Integration and Collaboration

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Partners, Subcontractors, and Collaborators

Joint Partnership: NREL and SNL

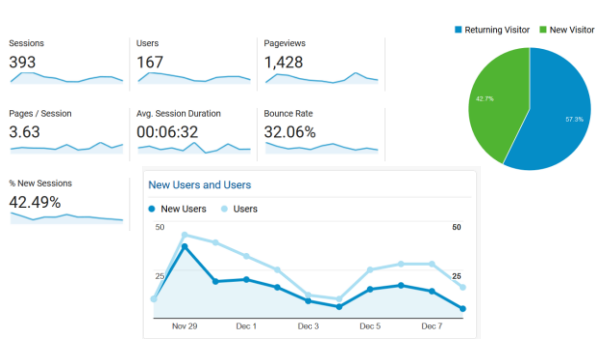
Subcontracts: Oregon State University, Andrews-Cooper, Penn State Applied Research Laboratory, and University of Texas at Austin

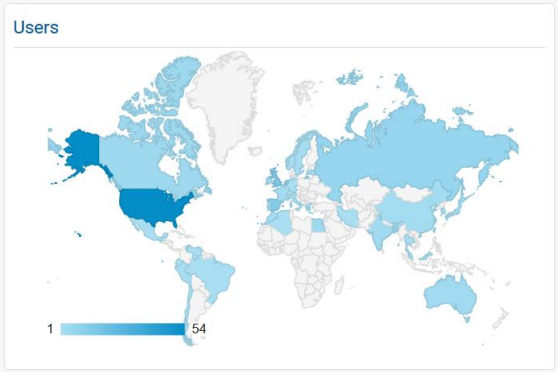
Communications and Technology Transfer

Open-Source Codes

- **WEC-Sim:** Available at https://github.com/WEC-Sim/WEC-Sim. The WEC-Sim site has **~170 unique visits per week**, and **20+ pull requests** (representative of contributions from outside collaborators) since 2014.

WEC-Sim Usage from 11/28-12/8





Users and Sessions by Country

Country	Users	Sessions
United States	50	114
United Kingdom	15	33
Spain	13	38
Netherlands	10	21
Russia	7	45
Taiwan	6	25
Canada	5	5
Egypt	5	6
Australia	4	12
India	4	6

- **The WEC Design Response Toolbox:** Available at https://github.com/WEC-Sim/WDRT

Research Integration and Collaboration

Communications and Technology Transfer (Continued)

Publications, Presentations and Other Technical Meetings

- Results and accomplishments from the Wave Energy Converter Modeling project have been documented in journals and presented at international conferences, including OMAE, International Society of Offshore and Polar Engineers, European Wave and Tidal Energy Conference, Marine Energy Technology Symposium, IEEE, OCEANS, and IEEE Power & Energy Society, with a total of 20+ publications and 10+ news articles

- A webinar of the ECM methodology was given for the Marine Energy Council in Q4 FY16

- A roundtable meeting with researchers from the Office of Naval Research community, NREL, and SNL has been scheduled for Q2 FY17

Industry Feedback

- **From OPT industry support project that utilized WEC-Sim:** "Through the collaboration, we were able to obtain valuable insight on the performance of some of our float configurations in order to further optimize their design and performance in terms of maximizing their wave energy capture"

Research Integration and Collaboration

List of Project Publications

WEC-Sim (available at: https://wec-sim.github.io/WEC-Sim/publications.html)

- Y. Yu, M. Lawson, K. Ruehl, and C. Michelen, "Development and Demonstration of the WEC-Sim Wave Energy Converter Simulation Tool," 2nd Marine Energy Technology Symposium, Seattle, WA, 2014.
- Y. Yu, Y. Li, K. Hallett, and C. Hotimsky, "Design and Analysis for a Floating Oscillating Surge Wave Energy Converter," OMAE 2014, San Francisco, CA, 2014.
- M. Lawson, Y. Yu, A. Nelessen, K. Ruehl, and C. Michelen, "Implementing Nonlinear Buoyancy and Excitation Forces in the WEC-Sim Wave Energy Converter Modeling Tool," OMAE 2014, San Francisco, CA, 2014.
- K. Ruehl, C. Michelen, S. Kanner, M. Lawson, and Y. Yu, "Preliminary Verification and Validation of WEC-Sim, an Open-Source Wave Energy Converter Design Tool," OMAE 2014, San Francisco, CA, 2014.
- M. Lawson, Y.-H. Yu, K. Ruehl, and C. Michelen, "Improving and Validating the WEC-Sim Wave Energy Converter Code," 3rd Marine Energy Technology Symposium, DC, 2015.
- N. Tom, M. Lawson, and Y. Yu, "Demonstration of the Recent Additions in Modeling Capabilities for the WEC-Sim Wave Energy Converter Design Tool," OMAE 2015, St. John's, Newfoundland, Canada, 2015.
- R. So, A. Simmons, T. Brekken, K. Ruehl, and C. Michelen, "Development of PTO-SIM: A Power Performance Module for the Open-Source Wave Energy Converter Code WEC-SIM," OMAE 2015, St. John's, Newfoundland, Canada, 2015.
- M. Lawson, B. Garzon, F. Wendt, Y. Yu, and C. Michelen, "COER Hydrodynamics Modeling Competition: Modeling the Dynamic Response of a Floating Body Using the WEC-SIM and FAST Simulation Tools," OMAE 2015, St. John's, Newfoundland, Canada, 2015.
- N. Tom, M. Lawson, and Y. Yu, "Recent Additions in the Modeling Capabilities for the WEC-Sim-v1.1 Wave Energy Converter Design Tool," ISOPE, Kona, HI, 2015.
- R. So, S. Casey, S. Kanner, A. Simmons, and Brekken, T. K. A., "PTO-Sim: Development of a Power Take Off Modeling Tool for Ocean Wave Energy Conversion," IEEE PES, 2015.
- A. Simmons, T. Brekken, P. Lomonaco, and C. Michelen, "Creating a Dynamometer for Experimental Validation of Power Take-Off Forces on a Wave Energy Converter," IEEE SusTech, 2015.
- A. Combourieu, M. Lawson, A. Babarit, K. Ruehl, A. Roy, R. Costello, P. L. Weywada, and H. Bailey, "WEC3: Wave Energy Converters modeling Code Comparison project," EWTEC 2015, Nantes, France, 2015.
- B. Bosma, K. Ruehl, A. Simmons, B. Gunawan, P. Lomonaco, and C. Kelley, "WEC-Sim Phase 1 Validation Testing—Experimental Setup and Initial Results," OMAE 2016, Busan, Korea, 2016.
- K. Ruehl, C. Michelen, B. Bosma, and Y.-H. Yu, "WEC-Sim Phase 1 Validation Testing—Numerical Modeling of Experiments," OMAE 2016, Busan, Korea, 2016.
- Sirnivas S., Yu Y.-H., Hall M., and Bosma B., "Coupled Mooring Analyses for the WEC-Sim Wave Energy Converter Design Tool," OMAE 2016, Busan, Korea, 2016.

ECM (available at: http://wec-sim.github.io/WDRT/publications.html)

- R.G. Coe, C. Michelen, A. Eckert-Gallup, Y. Yu and J. van Rij, "WDRT: A Toolbox for Design-Response Analysis of Wave Energy Converters," 4th Marine Energy Technology Symposium, Washington, DC, 2016.
- E. Quon, A. Platt, Y.-H. Yu, and M. Lawson, "Application of the Most Likely Extreme Response Method for Wave Energy Converters," OMAE 2016, Busan, Korea, 2016.
- A. C. Eckert-Gallup, C. J. Sallaberry, A. R. Dallman, and V. S. Neary, "Application of Principal Component Analysis (PCA) and Improved Joint Probability Distributions to the Inverse First-Order Reliability Method (I-FORM) for Predicting Extreme Sea States," Ocean Engineering 112, 307–19, 2016.
- C. Michelen, and R. Coe, "Comparison of Methods for Estimating Short-Term Extreme Response of Wave Energy Converters, " IEEE OCEANS 2015, Washington, D.C., 2015.
- Y.-H. Yu, J. Van Rij, R. G. Coe, and M. Lawson, "Development and Application of a Methodology for Predicting Wave Energy Converters Design Load," OMAE 2015, St. Johns, Canada, 2015.
- A. C. Eckert-Gallup, C. J. Sallaberry, A. R. Dallman, and V. S. Neary, "Modified Inverse First Order Reliability Method (I-FORM) for Predicting Extreme Sea States," Tech. Rep. SAND2014-17550, Sandia National Laboratories, Albuquerque, NM, 2014.
- R. Coe, V. Neary, M. Lawson, Y.-H. Yu, and J. Weber, "Extreme Conditions Modeling Workshop Report," Tech. Rep. NREL/ TP-5000-62305 SNL/ SAND2014-16384R, 2014.
- R. G. Coe, and V. S. Neary, "Review of Methods for Modeling Wave Energy Converter Survival in Extreme Sea States," 2nd Marine Energy Technology Symposium, Seattle, WA, 2014.

Next Steps and Future Research

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FY17/Current Research

WEC-Sim: Cultivate a broader WEC-Sim user/developer base and transfer ownership of WEC-Sim, including future developments and code maintenance, to industry developers and academic researchers to provide a well-validated foundation for the future technology innovation needs

ECM

- Perform design load case studies to formulate a cohesive repeatable methodology for ECM analysis that can be adopted by the WEC community
- Complete industry support FOA projects with reliable and survival analyses of the awardee WECs to help them accelerate the technology development by minimizing the design-loading uncertainty and potential deployment risk and establishing confidence to move the design concept forward

Educational Organization Support

- Work with universities and student organizations to establish an organization, and funding method, for supporting ocean renewable energy–related education in the United States

Proposed Future Research

- Lightweight composites, flexible materials, and innovative power take-offs and mooring designs are potential for WEC developers to further reduce levelized cost of energy and increase reliability
- To address the needs to look into these multi-physics challenges, modeling approaches are proposed:
  - Simplified multi-physics design optimization models
  - Coupling of numerical and physical modeling
  - High-fidelity CFD/finite element analysis models to capture complex nonlinear phenomena

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