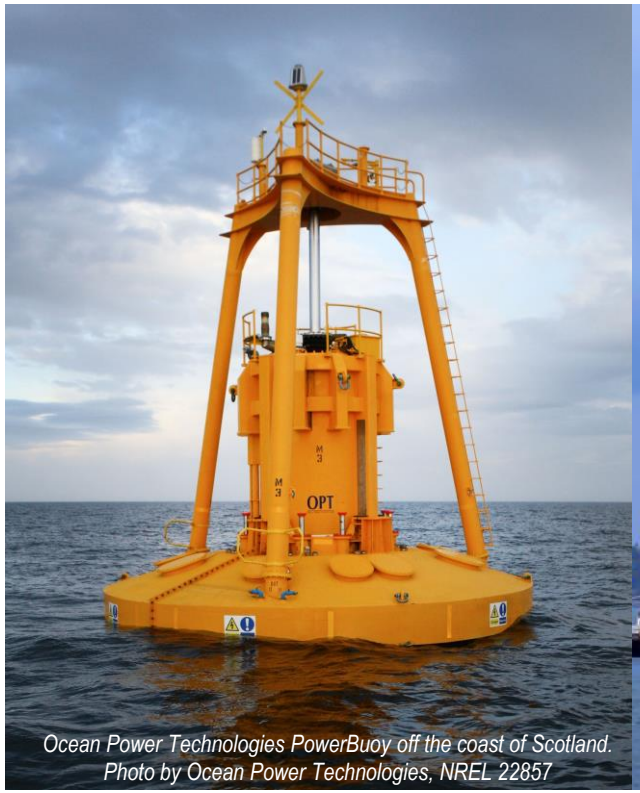
Water Power Technologies Office Peer Review

Marine and Hydrokinetics Program

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



Ocean Power Technologies PowerBuoy off the coast of Scotland.
Photo by Ocean Power Technologies, NREL 22857

Ocean Renewable Power's TidGen™ turbine generator unit Cobscook Bay, Maine.
Photo from Ocean Renewable Power Company. NREL 24507

MHK Industry Support

Ocean Power Technologies Float Optimization and Ocean Renewable Power TidGen™ Design Support

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Project Overview

MHK Industry Support:

The probability of success of lengthy and very expensive device development cycles in the nascent MHK industry will be increased by applying and building on the relevant experience gained and lessons learned in wind energy, through collaboration with the national laboratories.

The Challenge:

The emerging MHK sector has limited research and development budgets, little in-water device testing experience, few useful design tools, and numerous design challenges. The need is to efficiently leverage the experience gained in wind energy technology development and marine engineering to reduce risks and accelerate the commercialization of viable technologies.

Partners:

- Ocean Renewable Power Corporation (ORPC) – TidGen™ engineering and deployment
- Ocean Power Technologies (OPT) – PowerBuoy Float design
- Verdant Power – Kinetic HydroPower System blade design and test planning

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 & 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

Technology Maturity

- Conduct R&D for Innovative MHK components and systems
- Develop tools to optimize device and array performance and reliability

Crosscutting Approaches

- Exchange of data information and expertise

The Impact

OPT Collaboration

- Accelerated WEC design optimization with quantitative, repeatable comparison methodology
- Accurate, desktop design advancement with validated publically available design tool (WEC-Sim)
- Baseline levelized cost of energy (LCOE) estimation and pathway for design optimization for OPT PowerBouy

ORPC Collaboration

- Decreased risk and increased reliability and performance for TidGen™ and other ORPC products in development
- Cross-flow turbine optimization enabled with refined publically available CACTUS design tool
- Increased reliability industry-wide with MHK-specific Failures Modes and Effects Analysis, or FMEA, methodology

Technical Approach: ORPC

TidGen™ Design Review: *Completed in FY2014 prior to last Peer Review*

- Decades of experience in advancing wind and other renewable energy technologies efficiently leveraged through collaboration with the national laboratories
- Utilized experts in structural design, wind/MHK turbine design and operation, marine instrumentation, generators and power electronics, fluid mechanics, and wind turbine SCADA and "field" testing expertise
- Utilized institutional knowledge and tools and methods in advanced hydro-structural analysis leveraged from defense R&D.
- Provided guidance on system refinement based on simulations, and lab and field test results

Failure Modes, Effects and Criticality Analysis (FMECA)

- In-depth analysis of electrical system, operation and control and structural sub-systems of TidGen®
- Risk assessment of failure modes and recommended actions to prevent/mitigate impacts

Design Review and FMECA enabled identification of priority support areas

Technical Approach: ORPC

Key Specific Support Efforts Identified and Conducted

1. Electrical, Control and Measurement Systems Support: Guidance and feedback on SCADA and instrumentation systems designs, and generator design options

2. Foil Joint Refinement: Detailed review of TidGen™ foil joints including structural analysis of rotor. Perform hydro-elastic analysis to inform assessment and recommendations

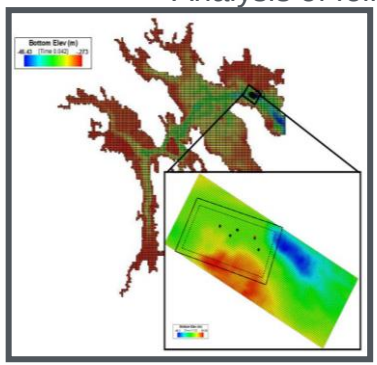
3. Array Optimization: Apply Sandia National Laboratories' Environmental Fluid Dynamics Code (SNL-EFDC) code to develop layouts to optimize energy production

4. Design Space Exploration: Utilize Sandia's Code for Axial and Cross-flow TUrbine Simulation (SNL CACTUS) model and compare to ORPC analyses to refine both simulation efforts and perform design space search to identify areas for potential improvement

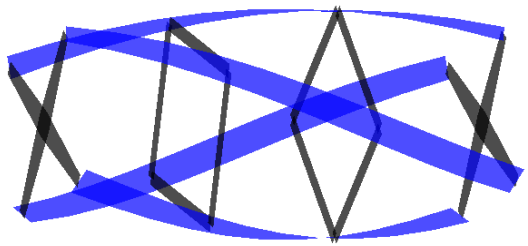
Accomplishments and Progress: ORPC

Project Completed

- Failure Modes Analysis
  - Delivered to ORPC September 2014 and utilized in subsequent development and deployment
  - MHK Risk Management Framework with refined FMECA methodology published, September, 2015
- Foil Joint Design Review
  - *Foil Joint Design Review Report* delivered to ORPC January, 2014
  - Hydro-elastic Analysis of TidGen™ Turbine: Bolt Analysis delivered to ORPC June 2014. This analysis revealed specific causes of join failures in open water test and informed design iteration
- Electrical System Support
  - Suggested instrumentation and SCADA design and operational approaches incorporated into subsequent designs/deployments
- Array Optimization
  - Array layouts provided to ORPC influencing array layout planning
- Design Space Exploration
  - Analysis of foil and strut designs options provided and informing ORPC product development



ORPC 5-unit array, Cobscook Bay



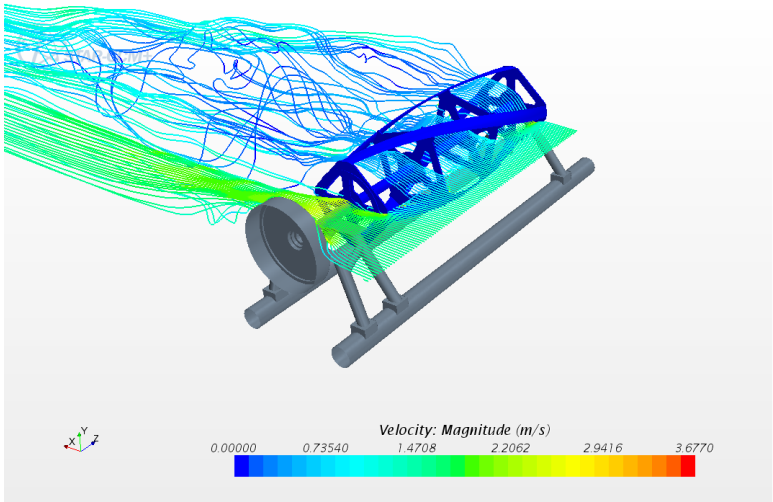
TidGen® Rotor

"NREL and SNL provided an independent assessment of our approach to technology development which allowed us to identify the strengths and weaknesses of our approach, allowing to move forward with higher confidence that our technology development path was fundamentally sound." -- Jarlath McEntee, Ocean Renewable Power Company, LLC

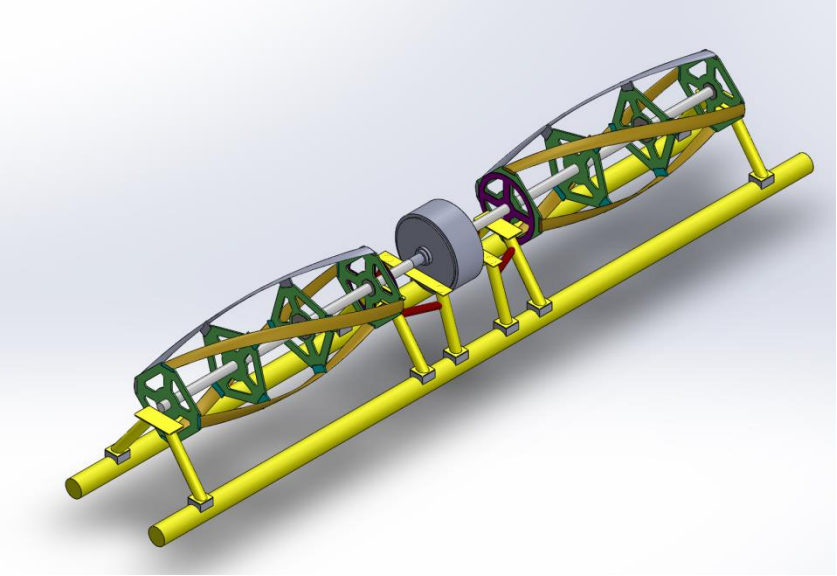
Accomplishments and Progress: ORPC

High Fidelity Evaluation of ORPC's RivGen® Cross-flow Turbine

- Demonstrated significant improvements to the RivGen® performance could be gained by a design which reduces the number of struts



Isometric view of RivGen® TGU



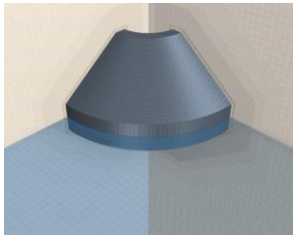
Vincent Neary, Principal Investigator
Carlos Michelen
Andrew Murphy
Ryan Coe

"The work performed on the RivGen analysis is a nice piece of work! Thank you for all of your good work!" -- Jarlath McEntee, Ocean Renewable Power Company, LLC

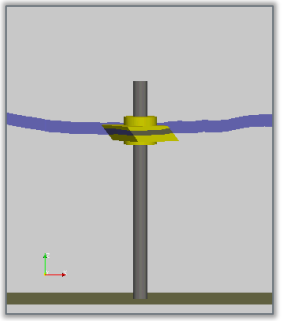
Technical Approach: OPT

Objective: Elucidate float design attributes for increased hydrodynamic performance

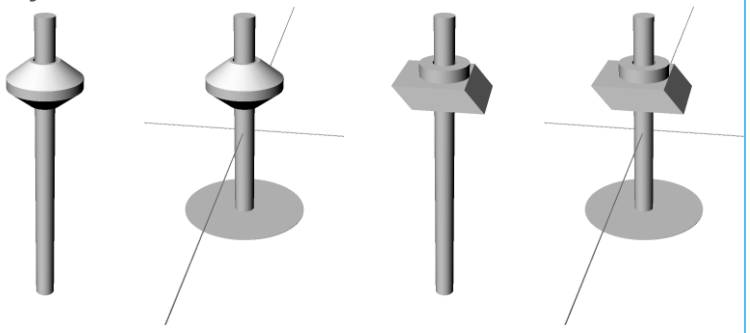
- **OPT – Float Shape Development and Tank Testing**
- **NREL – WEC-Sim (Wave Energy Converter Simulator) Model Setup and Validation**
  - WAMIT evaluation of linear hydrodynamic coefficients
  - CFD evaluation of viscous drag coefficients, C_D
  - Validation the of WEC-Sim model with OPT test data
- **NREL – Design Evaluation**
  - Assess design variations for power production, fatigue loading, extreme condition response ,and wave directionality
- **NREL – Design Comparison**
  - Compare design variations with key metrics
    - Power to Weight
    - Power to Fatigue Loads
    - Power to 100-year Extreme Response
    - Power to Planar Area
    - Power to Surface Area



CFD Evaluation of Float C_D's



Example WEC-Sim Simulation

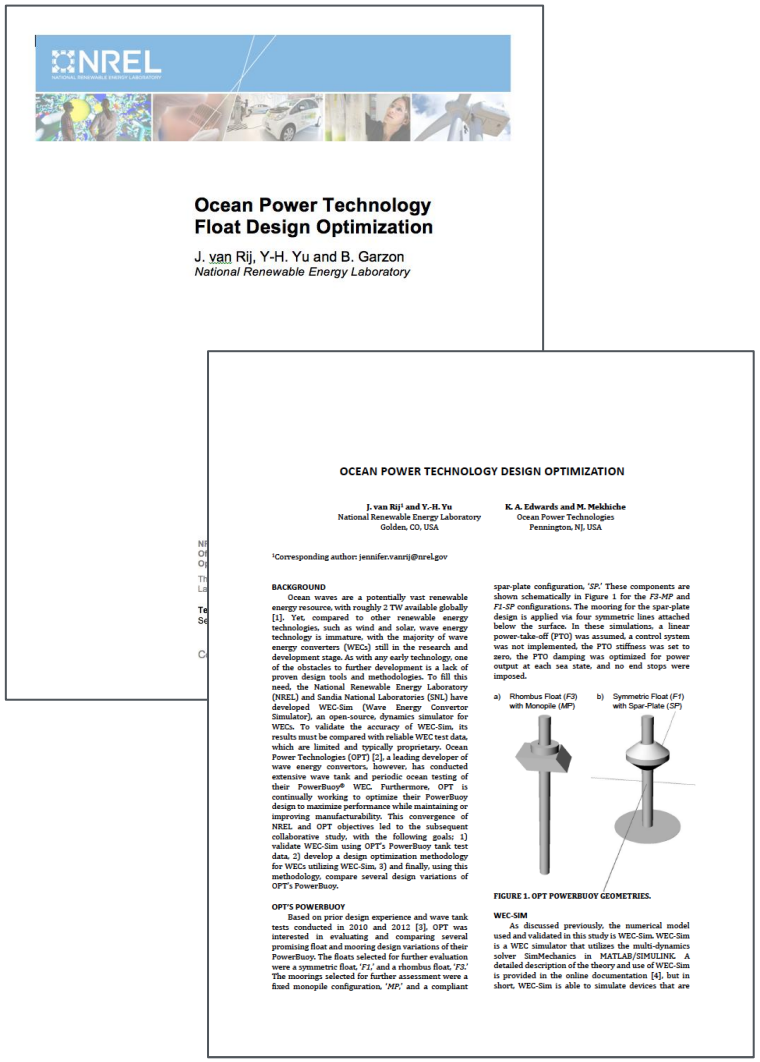


OPT WEC Design Variations Evaluated and Compared

Accomplishments and Progress: OPT

OPT Float Optimization

- Comparison completed of four designs based on key performance and survivability ratios: provided OPT baseline LCOE estimation and pathway for design optimization
- Publicly available WEC-Sim code validated with OPT's tank test data:
  - Greater confidence in accuracy of simulation results
  - Leveraged DOE supported wave tank test data
- Quantitative, repeatable wave energy convertor (WEC) design comparison methodology to facilitate efficient WEC design developed and published. Analyses also informed the DOE extreme condition modeling framework.



NREL

Ocean Power Technology Float Design Optimization

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National Renewable Energy Laboratory

OCEAN POWER TECHNOLOGY DESIGN OPTIMIZATION

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BACKGROUND

Ocean waves are a potentially vast renewable energy resource, with roughly 2 TW available globally [1]. Yet, compared to other renewable energy technologies, such as wind and solar, wave energy technology is immature, with the majority of wave energy converters (WECs) still in the research and development stage. As with any early technology, one of the obstacles to further development is a lack of proven design tools and methodologies. To fill this need, the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) have developed WEC-Sim (Wave Energy Convertor Simulator), an open-source, dynamics simulator for WECs. To validate the accuracy of WEC-Sim, its results must be compared with reliable WEC test data, which are limited and typically proprietary. Ocean Power Technologies (OPT) [2], a leading developer of wave energy convertors, however, has conducted extensive wave tank and periodic ocean testing of their PowerBuoy® WEC. Furthermore, OPT is continually working to optimize their PowerBuoy design to maximize performance while maintaining or improving manufacturability. This convergence of NREL and OPT objectives led to the subsequent collaborative study, with the following goals: 1) validate WEC-Sim using OPT's PowerBuoy tank test data, 2) develop a design optimization methodology for WECs utilizing WEC-Sim, 3) and finally, using this methodology, compare several design variations of OPT's PowerBuoy.

OPT'S POWERBUOY

Based on prior design experience and wave tank tests conducted in 2010 and 2012 [3], OPT was interested in evaluating and comparing several promising float and mooring design variations of their PowerBuoy. The floats selected for further evaluation were a symmetric float, '*F1*,' and a rhombus float, '*F3*.' The moorings selected for further assessment were a fixed monopile configuration, '*MP*,' and a compliant spar-plate configuration, '*SP*.' These components are shown schematically in Figure 1 for the *F3-MP* and *F1-SP* configurations. The mooring for the spar-plate design is applied via four symmetric lines attached below the surface. In these simulations, a linear power-take-off (PTO) was assumed, a control system was not implemented, the PTO stiffness was set to zero, the PTO damping was optimized for power output at each sea state, and no end stops were imposed.

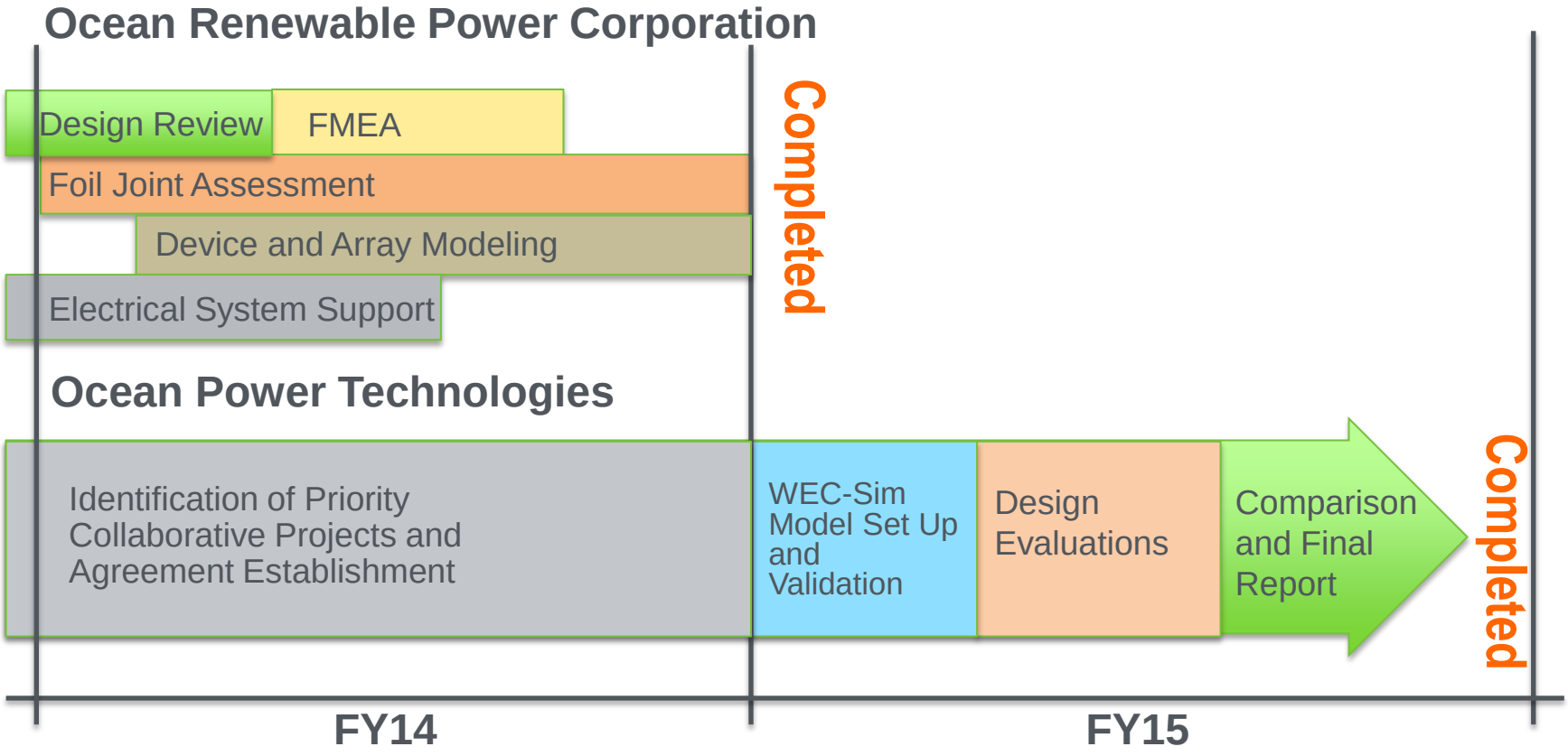
a) Rhombus Float (*F3*) with Monopile (*MP*) b) Symmetric Float (*F1*) with Spar-Plate (*SP*)

FIGURE 1. OPT POWERBUOY GEOMETRIES.

WEC-SIM

As discussed previously, the numerical model used and validated in this study is WEC-Sim. WEC-Sim is a WEC simulator that utilizes the multi-dynamics solver SimMechanics in MATLAB/SIMULINK. A detailed description of the theory and use of WEC-Sim is provided in the online documentation [4], but in short, WEC-Sim is able to simulate devices that are

Project Plan & Schedule: ORPC and OPT



- Verdant device deployment delayed – funding reallocated to support active projects
- All ORPC and OPT project work completed by end of FY15
- Identification of ORPC and OPT priority projects and establishing contractual agreements (Cooperative Research and Development Agreements) took much longer than anticipated

Project Budget: ORPC and OPT

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Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
NREL - $0 SNL - $0	$0	NREL - $0 SNL - $0	$0	NREL - $0 SNL - $0	$0

- NREL project effort funded by prior year carryover [FY14 effort =$191k and FY15 effort =$329k]
- SNL project effort funded by prior year carryover and completed in FY14 [FY14=$303k]
- Project was completed in FY2015

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

ORPC: Jarlath McEntee, Cian Marnagh
OPT: Kate Edwards, Mike Mekhiche
Verdant Power Corporation: Dean Corren
Montana State University: Erik Johnson
SEA Engineering: Craig Jones

Communications and Technology Transfer:

ORPC:

- *Proprietary: TidGen*™ Failure Modes, Effects, and Criticality Analysis Report, 9/30/14
- *Proprietary: TidGen*™ Foil Joint Design Review Report, 1/20/14
- *Proprietary:* Ross, M., B.C. Owens, C. Michelen and V.S. Neary. (2014). *Hydro-elastic Analysis of ORPC TIDGen® Turbine: Bolt Analysis. SAND2014*-17203, August, 2014. 68 pages.
- CACTUS: Disseminated code, user's manual and background material to over a dozen university and industry researchers. Launched several Github repositories to facilitate open source research and development. New copyright assertion agreement (under review) will allow release of new version of code with added capabilities.
- MHK Risk Management Framework: http://www.nrel.gov/docs/fy15osti/63258.pdf

OPT:

- *Proprietary: Summary Report- Comparison of four OPT designs based on key performance and survivability ratios, delivered to OPT, 9/30/2015*
- *Ocean Power Technology Design Optimization*, J. van Rij, Y.-H. Yu, K.A. Edwards, M. Mekhiche, Proceedings of the 4TH Marine Energy Technology Symposium (METS), Washington, DC, USA, January 2016 – http://events.pennwell.com/nha2016/Public/Calendar.aspx?ID=53123&TrackID=1406,1407,1323
- WEC-Sim: http://wec-sim.github.io/WEC-Sim/

Next Steps and Future Research

FY17/Current research:

Project was completed in FY16.

Proposed future research:

Support MHK technology development projects in relevant areas of national laboratory expertise to reduce risks and increase projects' probability of success:

- Design review and guidance
- Simulation and analysis
- Component and subsystem testing
- Open-water testing/measurement/monitoring

Present mechanisms for supporting industry efforts include:

- Technical Services Agreement – fee for service
- DOE Small Business Vouchers Program
- DOE Water Power Funding Opportunity Announcements
- DOE SBIR/ARPA-E