SAND2016-10739C

Exceptional service in the national interest

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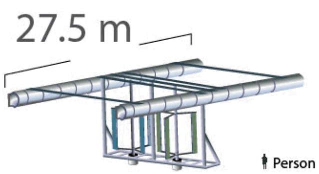
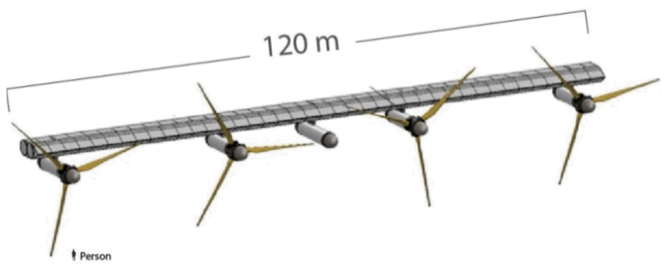
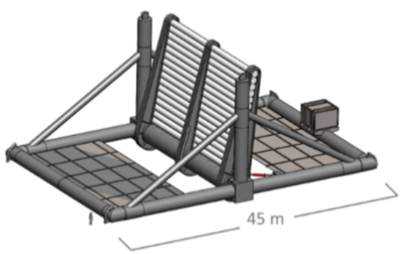
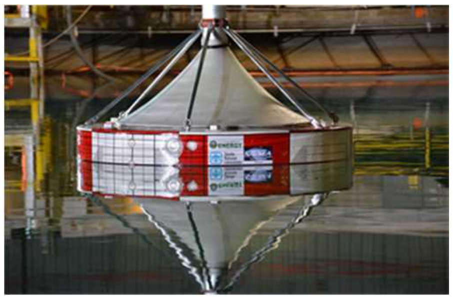








Marine Energy Conversion Technologies:

Lowering the Levelized Cost of Energy through Control Systems, Materials Research and Systems Engineering

Peter H. Kobos, Vincent S. Neary, Ryan G. Coe, Bernadette A. Hernandez-Sanchez
Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

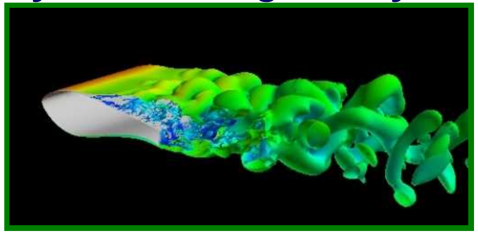
Outline*

- **Marine Hydrokinetics Technology**
- **Reference Model Project**
  - LCOE development for various devices
- **Advanced Controls**
  - Increased performance from various controls strategies
- **Advanced Materials**
  - Example Applications
- **Concluding remarks**

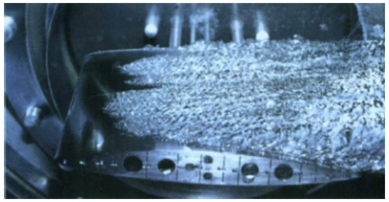
* Select presentation materials adapted from Neary et al., 2016.

MHK Research Focus Areas at Sandia National Labs

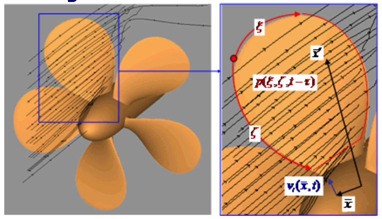
Hydrofoil Design/Analysis



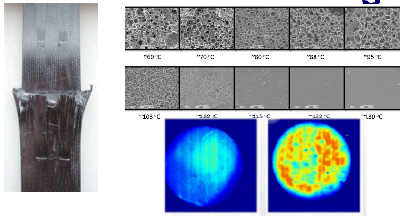
Cavitation



Hydro-Acoustics



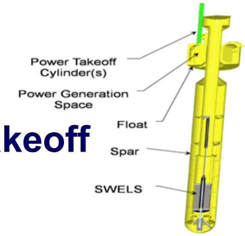
Materials & Coatings



Performance Modeling

Rotor Design & Testing

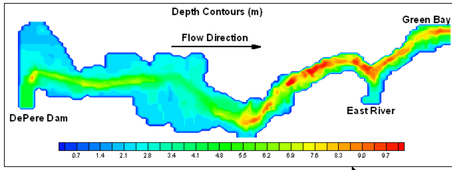
Power Takeoff Testing



Columbia Power 1/15th Scale Test (OSU)

Water Tunnel (PSU/ARL)

Coupled Device Array and Environmental Analysis



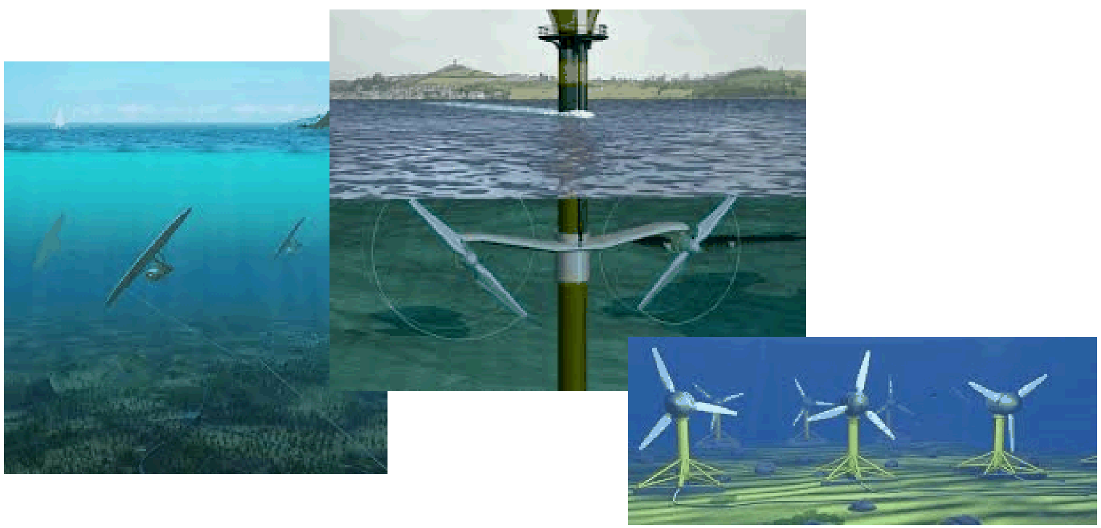
SNL EFDC

Technology Development Cycle

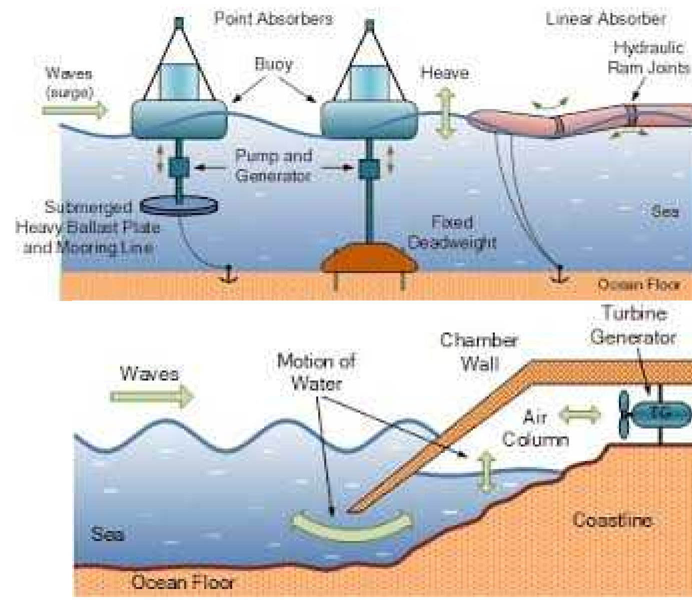
Components | Sub-systems | System Testing | Deployment

Reference Model Project

- Motivation:
  - Marine energy renewable, low-carbon resource
  - Dozens of proprietary design concepts
- Objectives
  - Design non-proprietary MEC devices for R&D
  - Benchmark cost of energy
  - Identify knowledge gaps, cost drivers



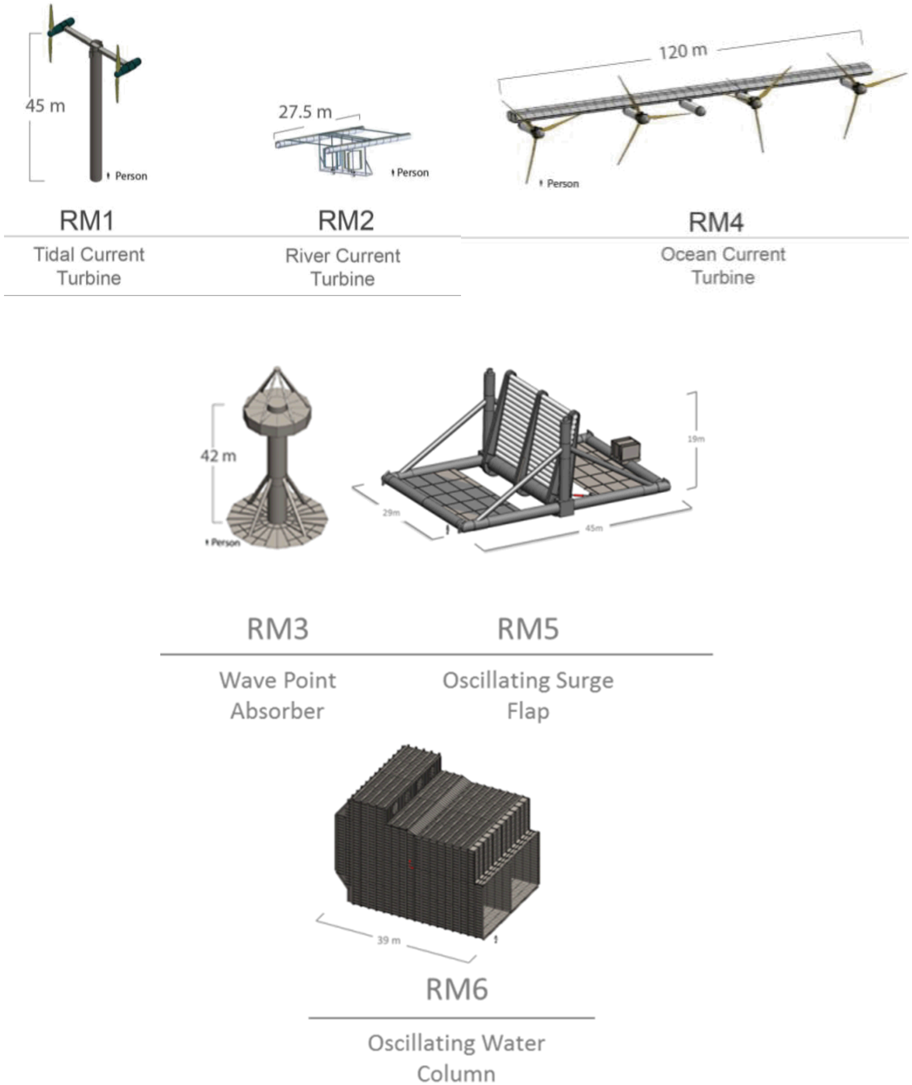
current energy converters (CEC)



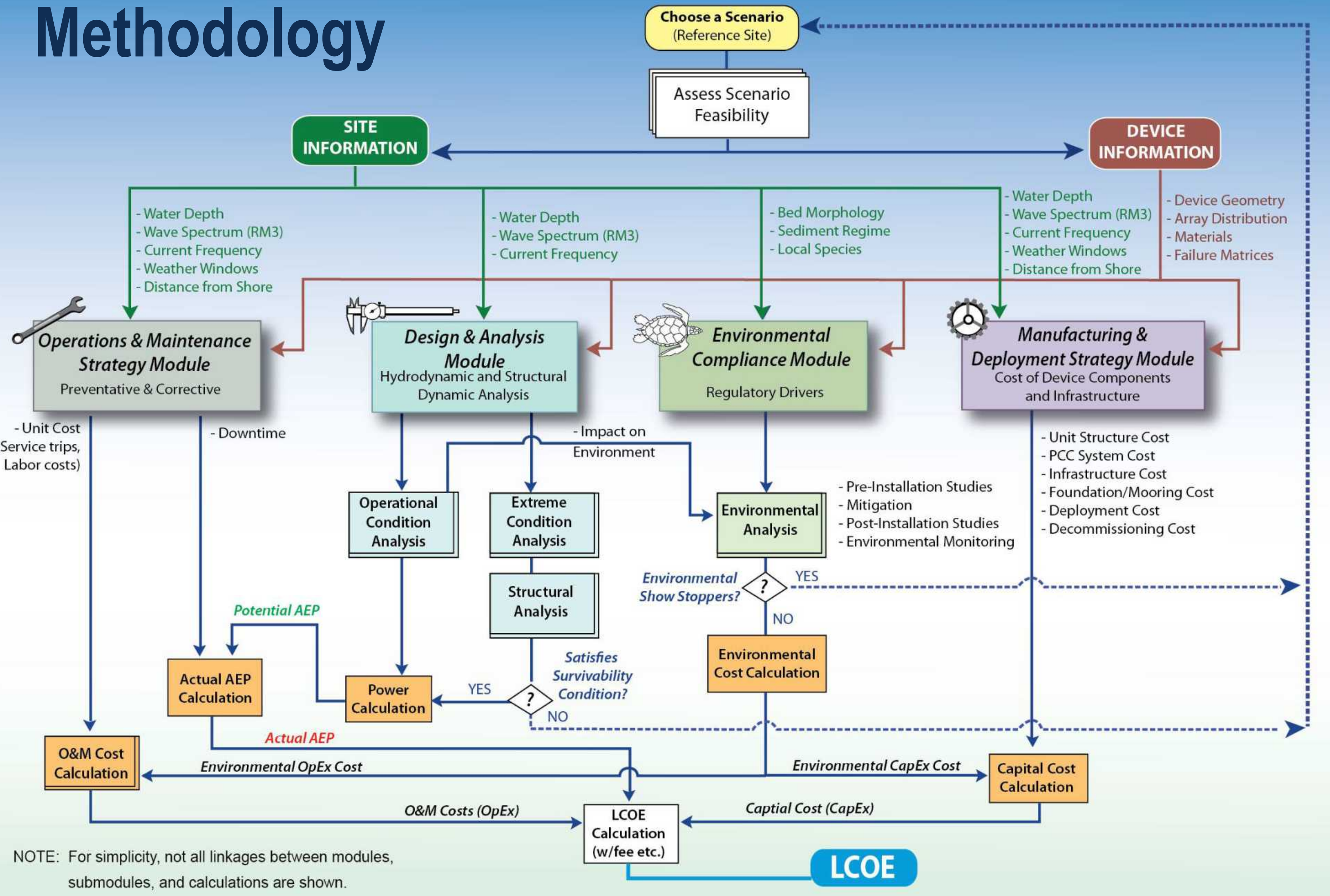
wave energy converters (WEC)

Reference Models

- Non-Proprietary Devices
  - 3 Current Energy Converters (CECs)
  - 3 Wave Energy Converters (WECs)
- Point Designs
  - Reference resource site
  - Utilizing "today's" technology
  - http://energy.sandia.gov/rmp



Methodology



NOTE: For simplicity, not all linkages between modules, submodules, and calculations are shown.

LCOE Formula

- Levelized Cost of Electricity
  - Denotes "Break Even" cost assuming minimum rate of return.

- 4 Primary Inputs
  - Capital Expenditures (CapEx)
    - Year 0 costs
  - Operational Expenditures (OpEx)
    - Year 1 to n costs
  - Average Annual Energy Production (AEP)
  - Fixed Charge Rate (FCR)
    - 10.8%
    - Lumped financing term including discount rate, inflation, taxes, depreciation, and project life.

- Analysis Performed for 1, 10, 50 and 100 – unit arrays

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

LCOE Formula (CapEx Categories)

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

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

LCOE Formula (OpEx Categories)

Sandia National Laboratories

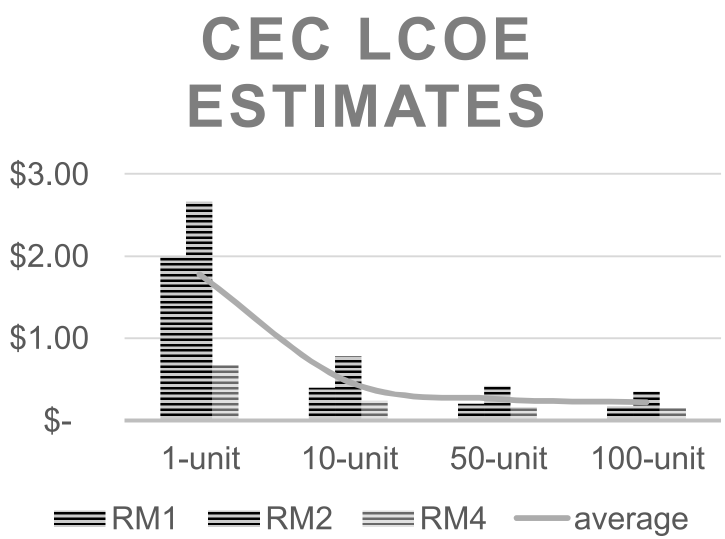
- Marine Operations & Maintenance (O&M)
- Shore-side Operations & Maintenance (O&M)
- Post Installation Environmental O&M
- Replacement Parts
- Consumables
- Insurance

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

Results - LCOE Overview

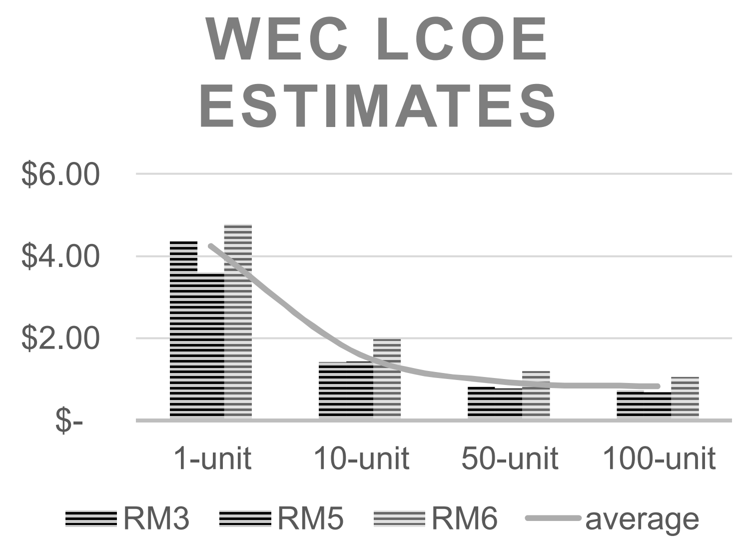
- CECs

	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



- WECs

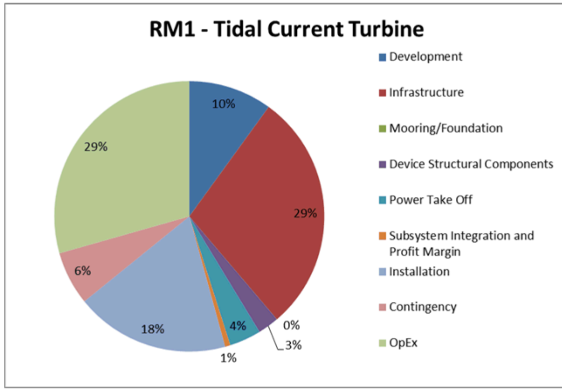
	1	10	50	100
RM3	$ 4.36	$ 1.41	$ 0.83	$ 0.73
RM5	$ 3.59	$ 1.44	$ 0.77	$ 0.69
RM6	$ 4.79	$ 1.98	$ 1.20	$ 1.06
average	$ 4.25	$ 1.61	$ 0.93	$ 0.83

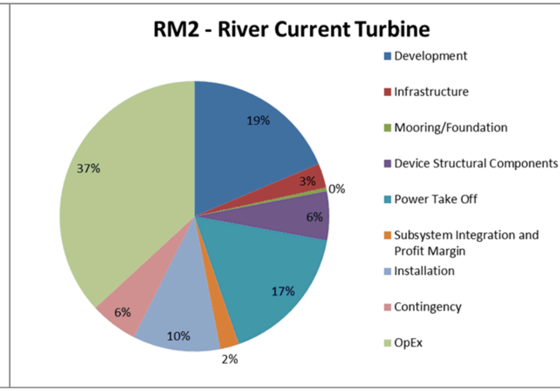


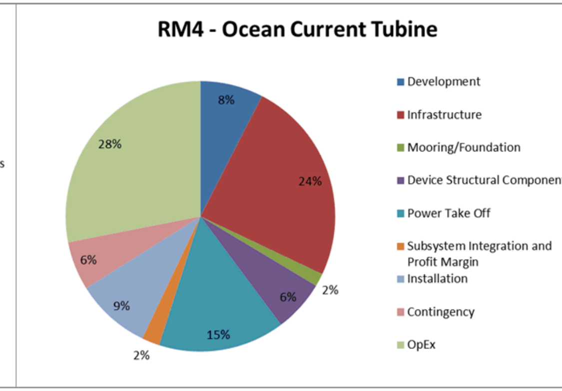
$/kWh

Results – CEC Breakdown

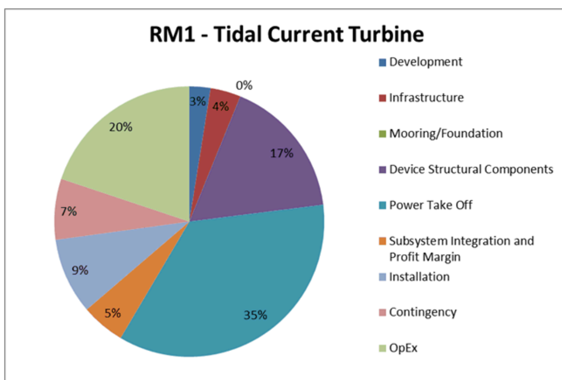
- 1-unit
  - O&M (green) & Infrastructure (red) dominate tidal & ocean current LCOE
  - O&M (green), Development (blue) & PTO (marine) dominate river current LCOE

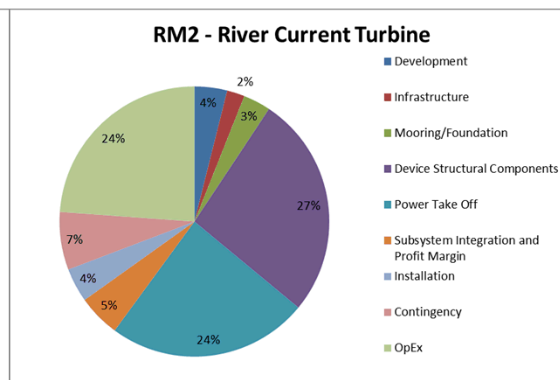


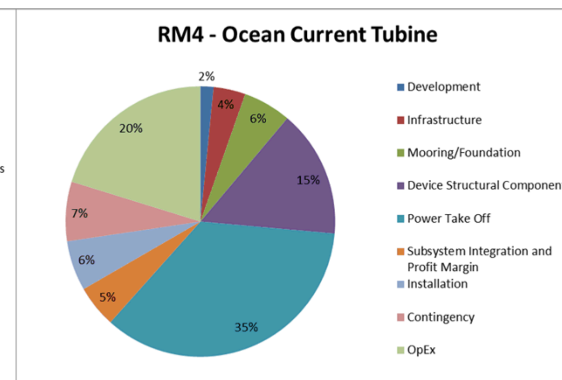




- 100-unit
  - PTO (marine), Structure (purple), and O&M (green) dominate LCOE

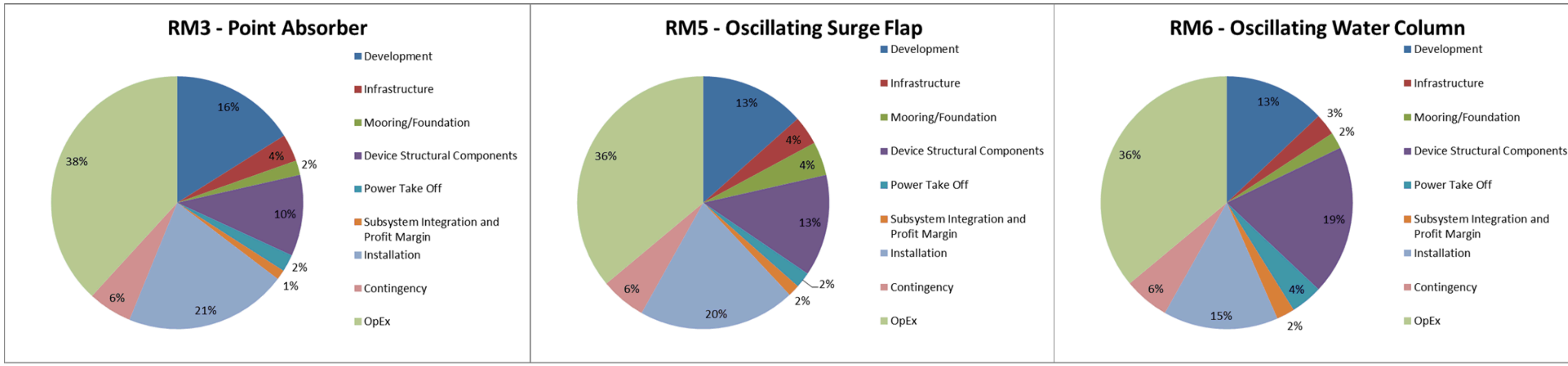




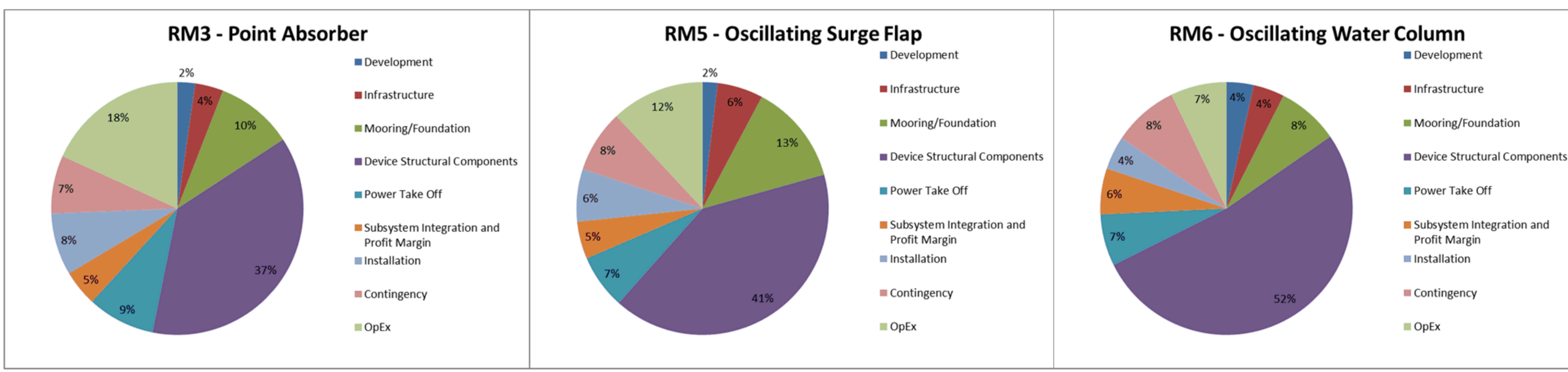


Results – WEC Breakdown

- 1-unit
  - O&M (green), Development (blue), and Installation (lavender) are LCOE drivers

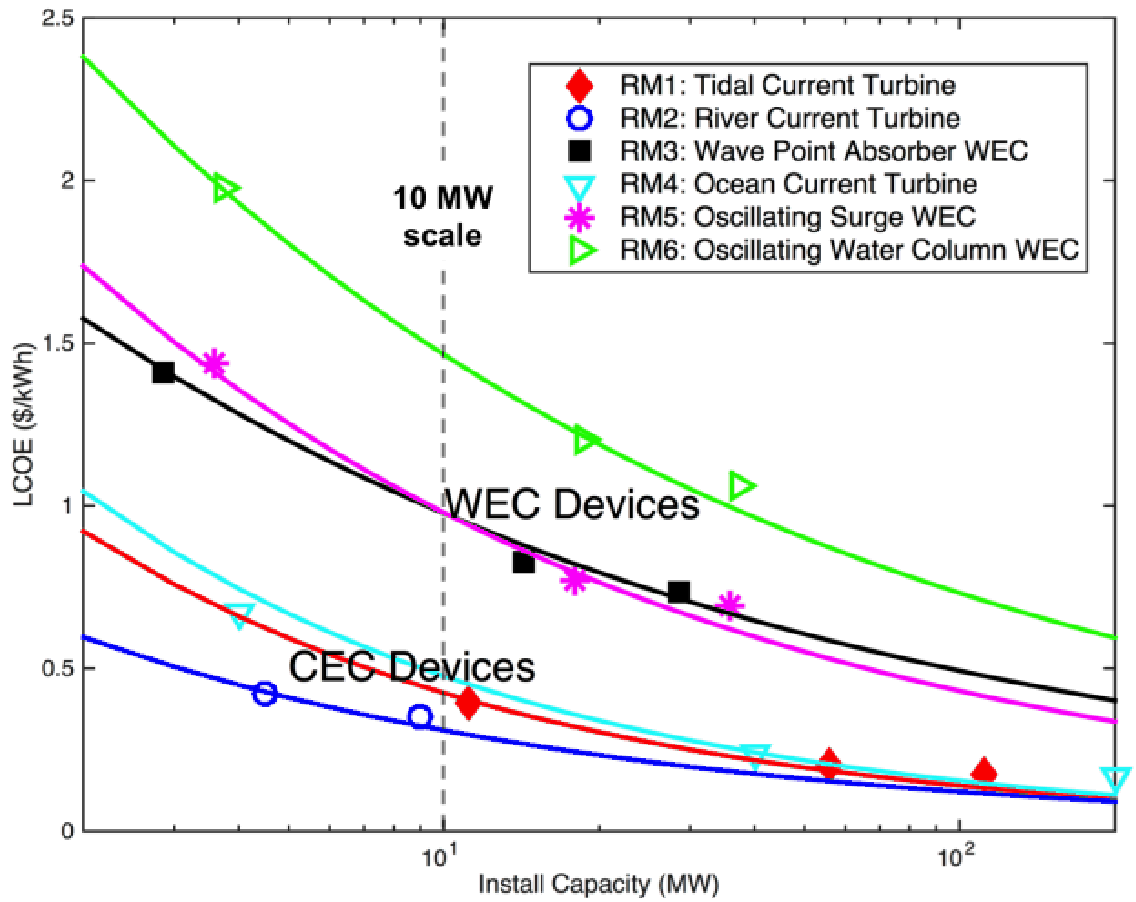


- 100-unit
  - Structure (purple) is primary cost driver, which is driven by large structural mass

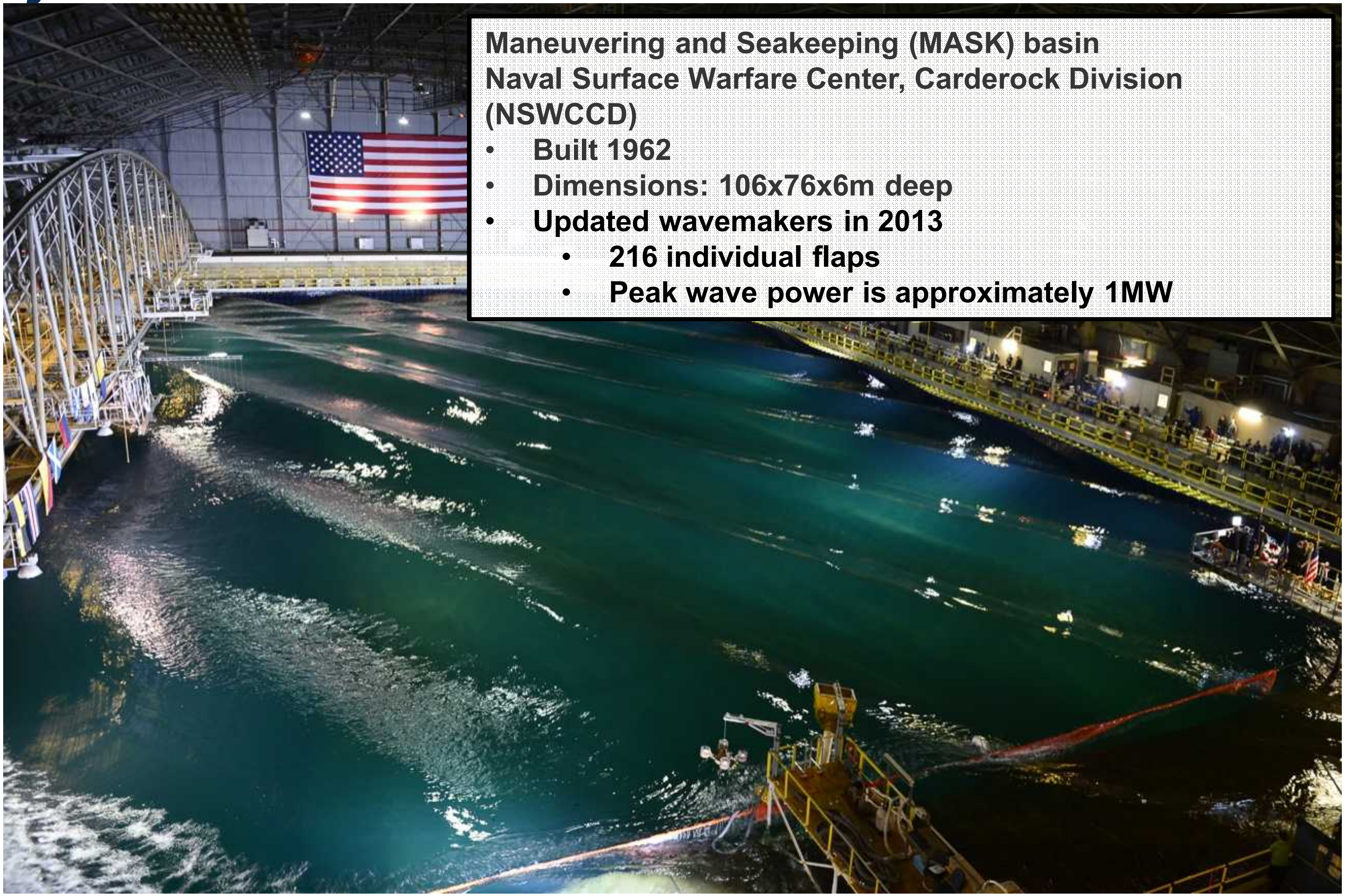


Results – 10 MW Installed Capacity

- 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.



Wave Energy Converter (WEC) – Controls Project: Test hardware – wave basin



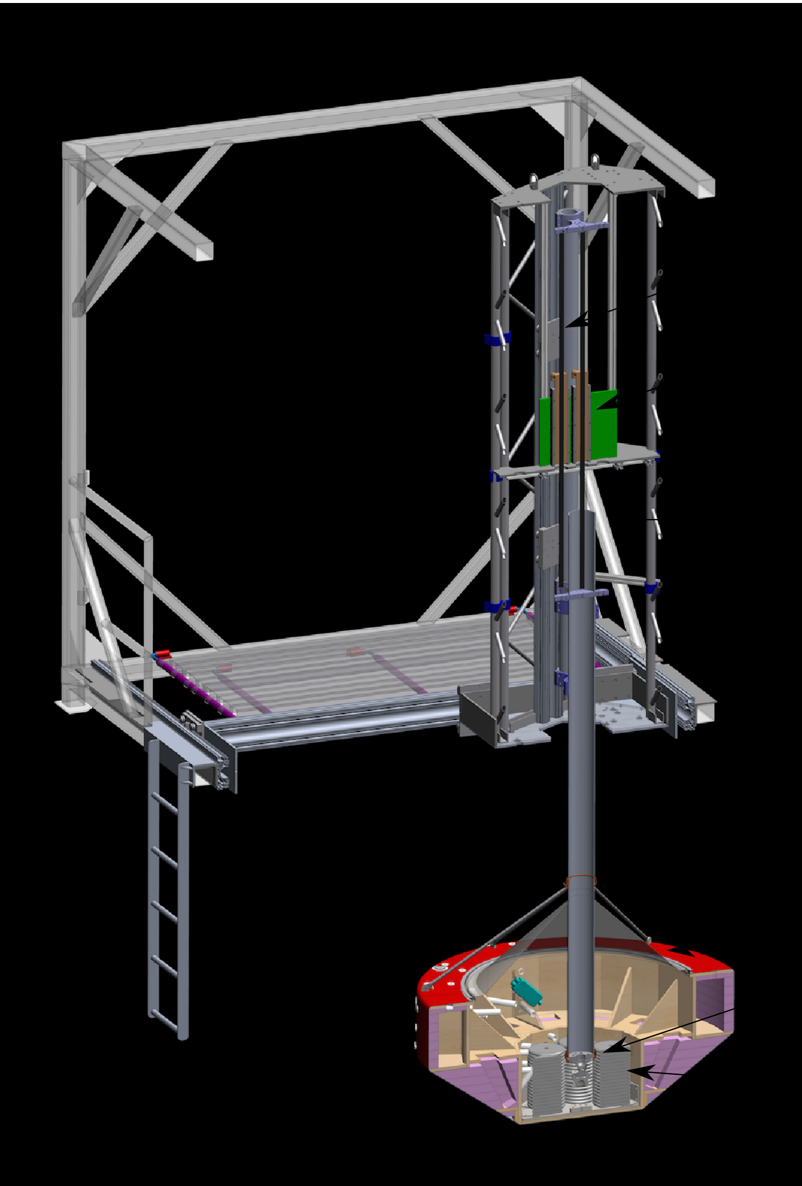
Maneuvering and Seakeeping (MASK) basin
Naval Surface Warfare Center, Carderock Division (NSWCCD)

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

Project motivation

- Project goal: accelerate/support usage of advanced WEC control by developers
- Numerous studies have shown large benefits of more advanced control of WECs (e.g., Hals et al. showed 330% absorption increase)
- Most studies rely on significant simplifications and assumptions
  - Availability of incoming wave foreknowledge
  - 1-DOF motion
  - Linear or perfectly know hydrodynamics
  - No sensor noise
  - Unlimited actuator performance

Test hardware – WEC device



dment

cal carriages

r stators

PCC tower

sliders

lanar motion table

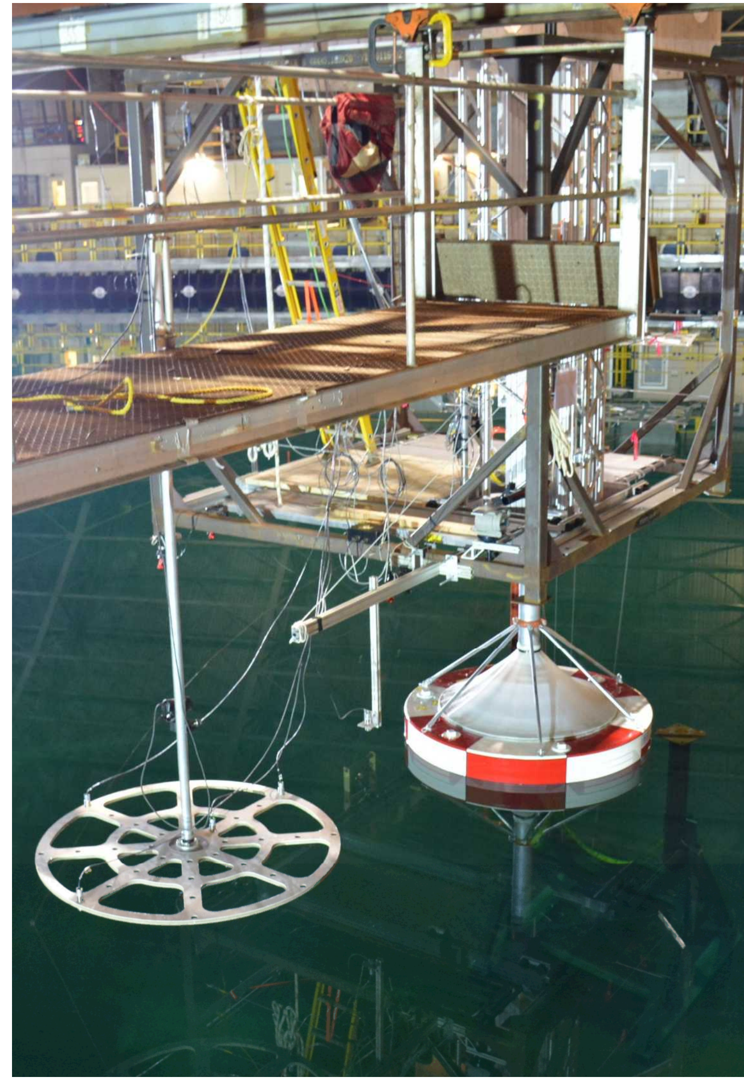
down-tube

tation lockout bars

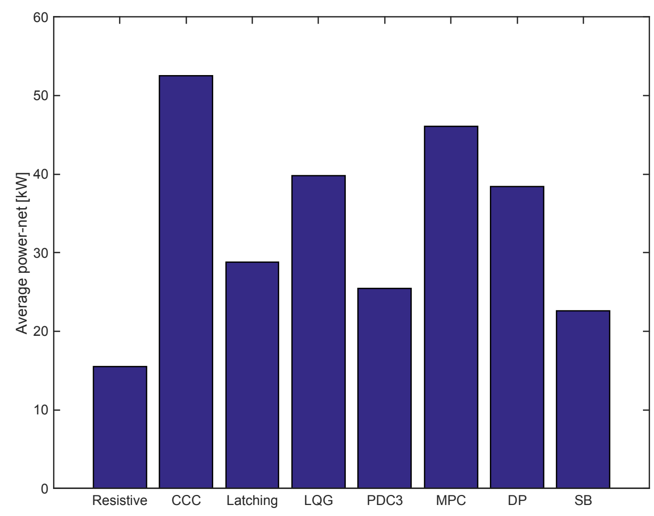
ave seal

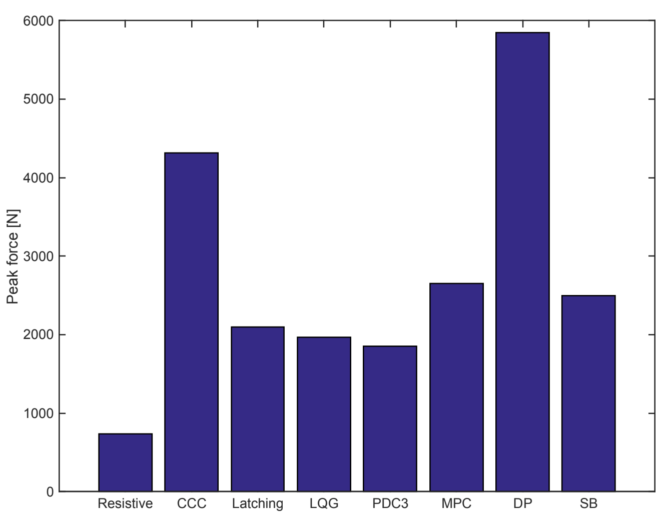
int

ast plates



Summary of results





Power increase of >330%

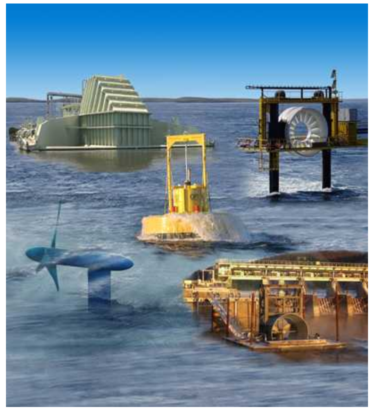
	Resistive	CCC	Latching	LQG	PDC3	Linear MPC	DP	SB
Power production characteristics								
Average power-in	0	279	0	46.5	45.8	98.8	374.8	39.0
Average power-net	15.5	52.5	28.8	39.8	25.5	46.1	38.4	22.6
Average energy-stored	0	251	0	27.5	42.9	76.4	332.9	23.8
Power-in, peak/RMS	0.0	5.8	0.0	5.6	5.1	5.6	5.4	4.3
Power-net, peak/RMS	7.3	38.8	6.2	14.3	17.3	20.2	60.1	16.2
Total absolute power flow	15.5	313.3	28.8	76.0	91.5	131.8	384.9	54.5
PCC requirements								
PCC force, peak	739	4312	2099	1970	1854	2653	5850	2500
Slew rate requirements	2.8 E+3	1.1 E+3	1.5 E+6	5.9 E+3	4.5 E+3	7.0 E+3	1.2 E+3	5.5 E+3
PCC force, RMS	315	2367	923	915	1086	1401	2730	1010
PCC Force, peak/RMS	2.35	1.82	2.27	2.15	1.71	1.89	2.14	2.49
Mechanical loading								
Oscillation amplitude, peak	0.06	0.25	0.10	0.14	0.11	0.17	0.28	0.12
Oscillation amplitude, peak/RMS	2.52	1.97	2.05	2.27	1.89	2.09	1.99	2.52
Oscillation velocity, peak	0.14	0.47	0.30	0.31	0.22	0.35	0.50	0.22
Oscillation velocity, peak/RMS	2.63	2.20	2.77	2.43	2.30	2.33	2.17	2.6
Oscillation acceleration, peak	0.39	1.02	0.45	0.78	0.22	0.46	1.27	0.64
Oscillation acceleration, peak/RMS	2.70	2.39	1.21	2.58	2.30	1.95	2.36	2.56

All units in metric

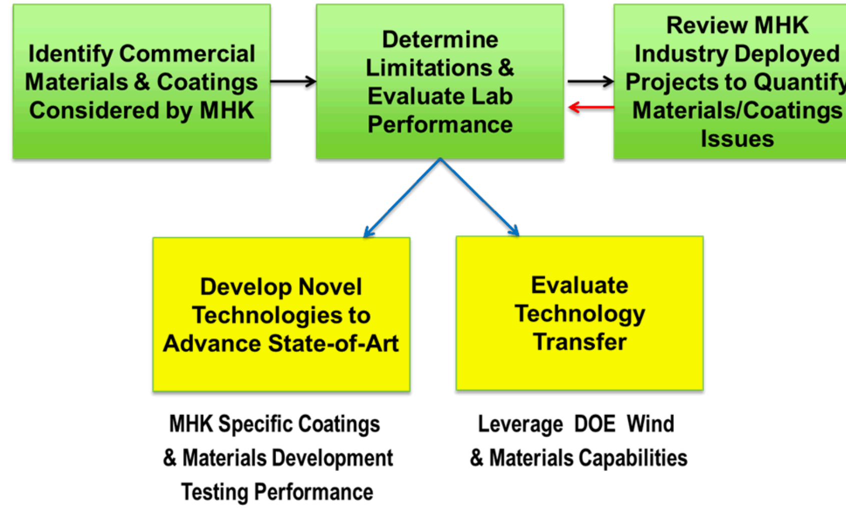
Advanced Materials for Marine Hydrokinetic (MHK) Technology

Purpose:

Applied research and provides guidance on Materials & Coatings to enable viability, lower the cost of energy (COE), and accelerate commercialization of marine and hydrokinetic technology (MHK).



Procedure:



Early Program Addressed:

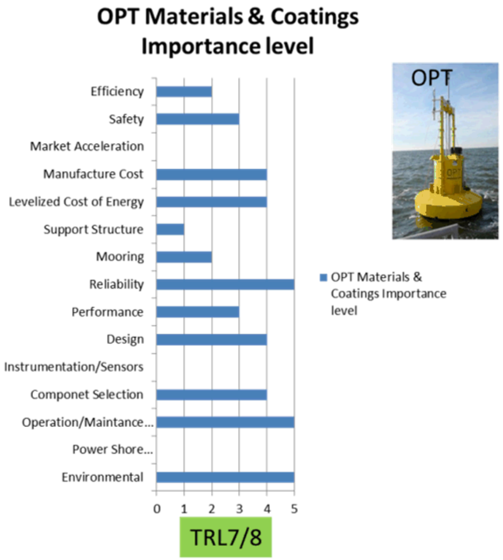
- Industrial Survey on Materials & Coatings
- Development & Characterization of MHK Specific Protective Coatings
- Materials Reliability & Performance Testing
- Initial Assessment of Underwater NDI Monitoring
- Meeting with Industry/Researcher coatings community
- MHK Composites Workshop

Future Program to Address:

- Removing Uncertainty & Barriers of using Composites (Industry Directed)
- Leverage Coatings Research & Library
- Understand Materials & Coatings Impact on MHK Manufacture, O&M, Reliability, Safety, Cost
- Support MHK Developers on Their Deployments

MHK Advanced Materials & Coatings

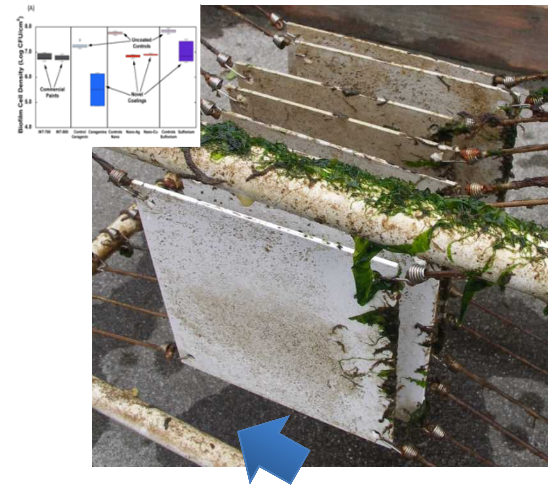
MHK Industrial Review



Water Power Materials Science & Engineering

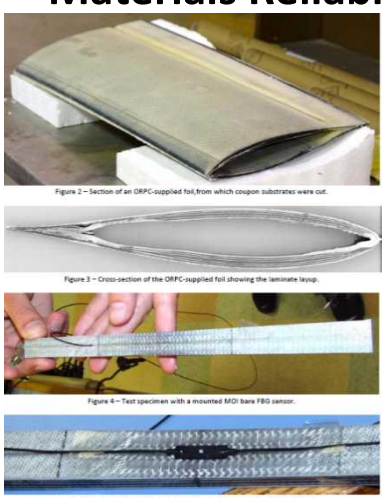
PNNL Marine Science Laboratory

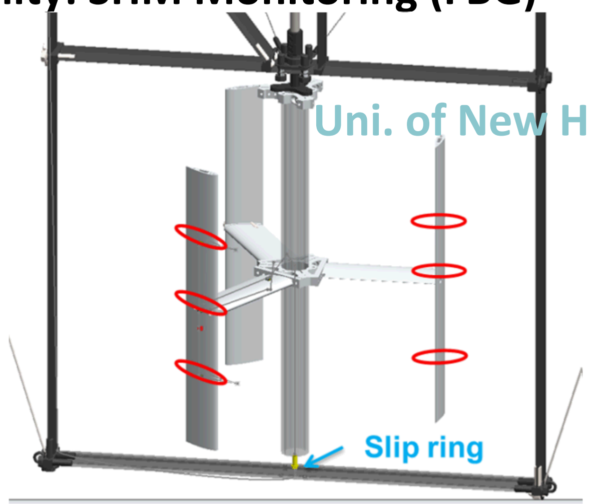
Protective Coatings



PNNL Open Water Testing

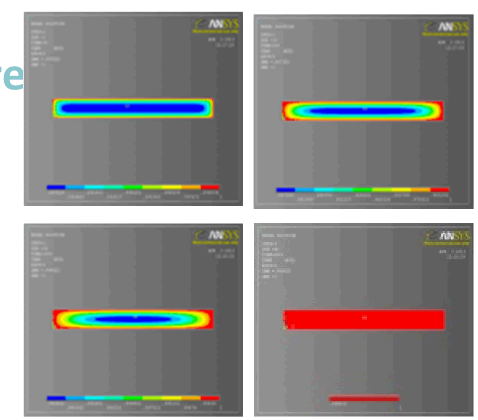
Materials Reliability: SHM Monitoring (FBG)





Uni. of New Hampshire

MHK Composite Performance



Ocean Renewable Power Co. / MSU

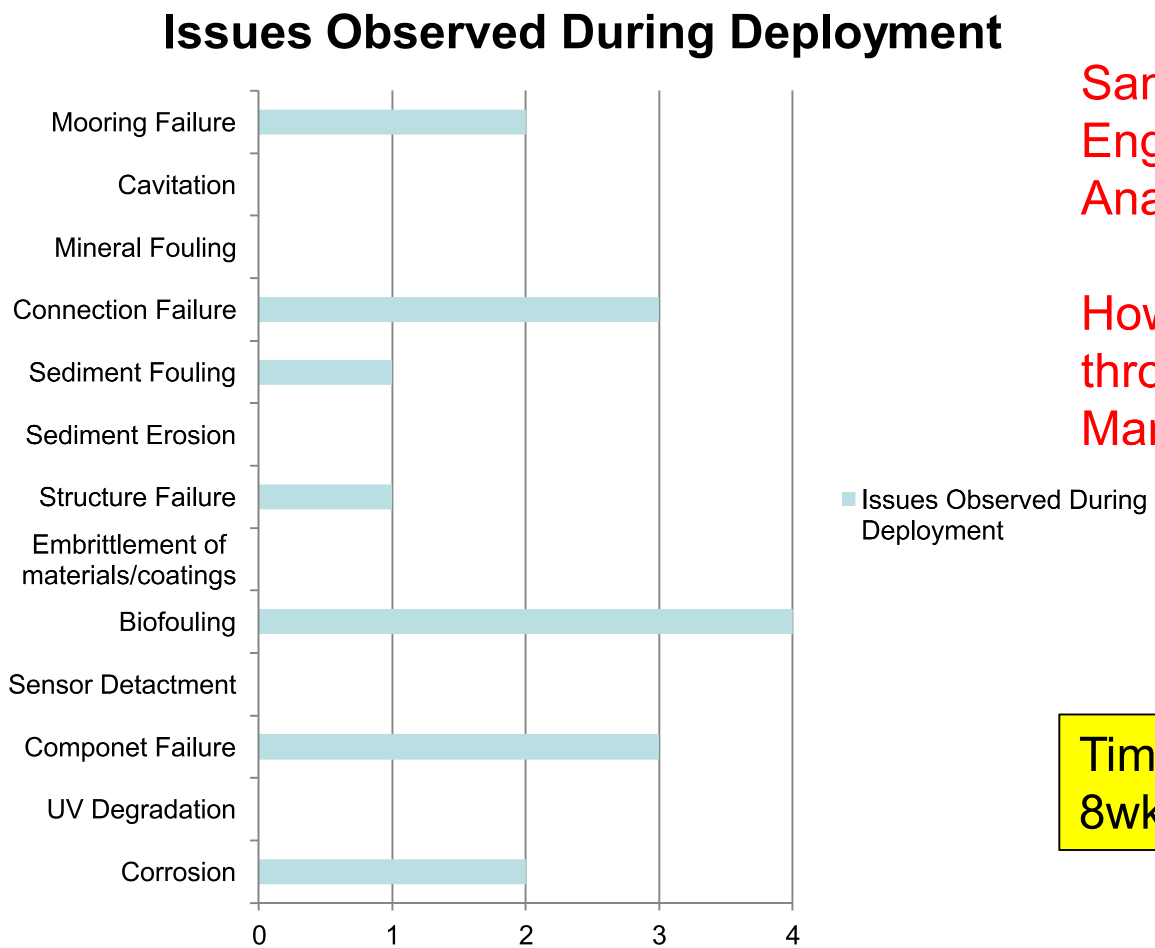
Montana State University (MSU)

Sandia Industrial Survey on Materials & Coatings

- Coatings ($/mass) = $8/kg for epoxy; $30/kg for Copper based coating. $130/gal for paint system color
- No or limited Nondestructive Inspection (NDI) and Inspection Analysis after manufacture/prior to deployment
- Carbon Composites-interest, but high cost
- Not all the materials used for deployment will be the same for manufactures. (not yet determined)

Sandia National Laboratories

Question to Companies: Did any of the following Issues Occur During the Deployment/Test Period (check all that apply).



Sandia, as a lab, is exploring Engineered Reliability & Forensics Analysis of Reliability.

How can prevent these issues through Materials, Process, & Manufacture?

Time of deployment:
8wks, 1yr, 3yr, <9,000 turbine hrs.

4 companies responded, each response was accounted to provide number of issues (1-4)

Upcoming Composites Research

Past Work

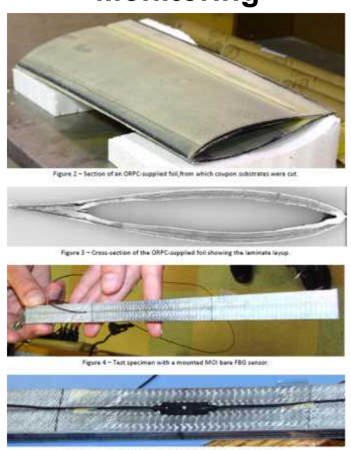
- Research and analysis of composite materials and coatings in operating environment (i.e. sea water). **SNL, PNNL, MSU, BYU, NDSU, ORNL (Toxicity)**

Material Design Tools for Marine Hydrokinetic Composite Structures (SNL, PNNL, NREL, MSU, FAU)

- Helping MHK industry reduce uncertainty in using composites
- Developing U.S. DOE MHK Composite Materials & Structures Database: http://energy.sandia.gov/energy/renewable-energy/water-power/technology-development/advanced-materials/mhk-materials-database/
- Mitigating biofouling & metal-carbon fiber interconnect corrosion in saltwater
- Examining MHK load challenges on material & substructure performance
- Examine impact on LCOE

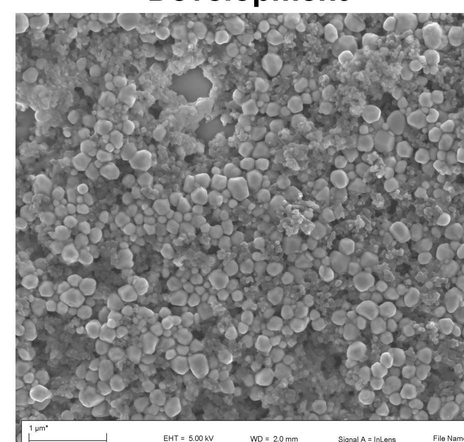
Biofouling & Marine coatings assessment

Structural Health Monitoring

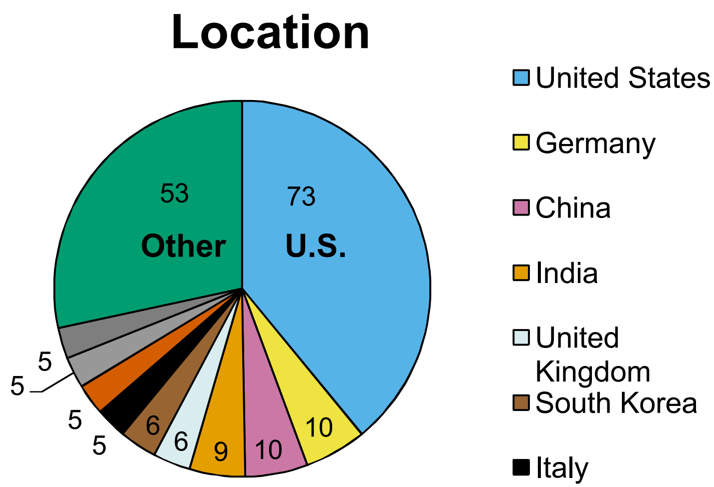


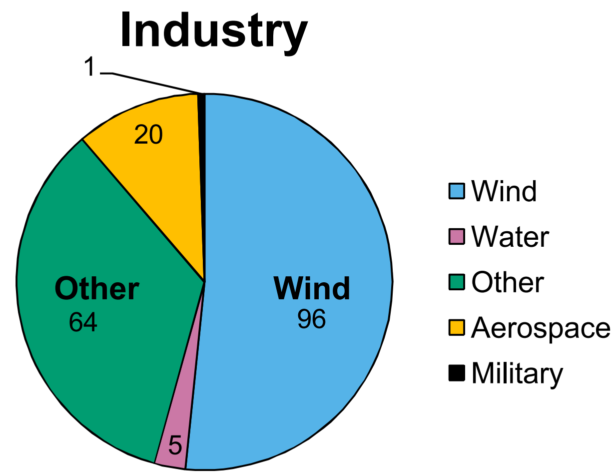
MHK Environmental Effects on Composites

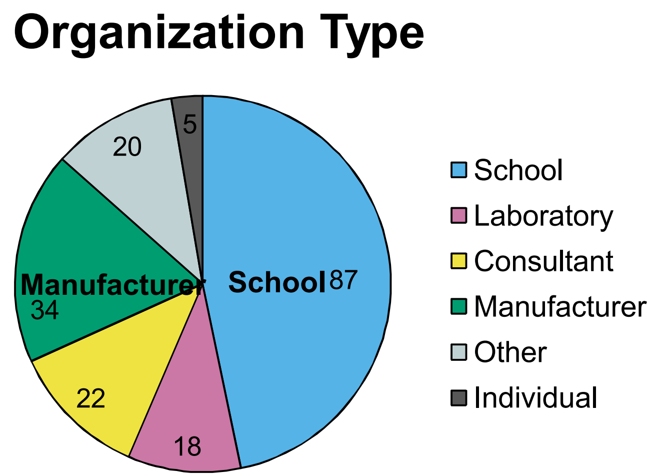
Nanomaterials Development



DOE/SNL/MSU Wind & Water Database







Current User Community of U.S. DOE Materials & Structures Database

Concluding Remarks

→ **Reference Models (LCOE)**

Current Energy Converters

- Close to market readiness:
  - Average 100-unit array LCOE ≈ $0.22/kWh
- Cost drivers: Power Takeoff, Structure, O&M

Wave Energy Converters

- Farther from market readiness:
  - Average 100-unit array (approximately 30 MW) LCOE ≈ $0.83/kWh
- Cost drivers: Structure, Mooring, O&M
- Need to increase Annual Energy Production (AEP) through improved energy capture

→ **Advanced Controls:** systems may increase power production substantially (300%+)

→ **Materials Research:** may provide longevity & cost reductions

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 (D. Scott Jenne & Yi-Hsiang Yu (NREL)), 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 multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References

- Neary, V., Kobos, P., Jenne, D.S. and Y-H Yu, 2016, Levelized Cost of Energy for Marine Energy Conversion (MEC) Technologies, EPRC[6], Santa Fe, NM, September 8-9, 2016.

THANK YOU

BACKUP SLIDES

RM Current Energy Converters

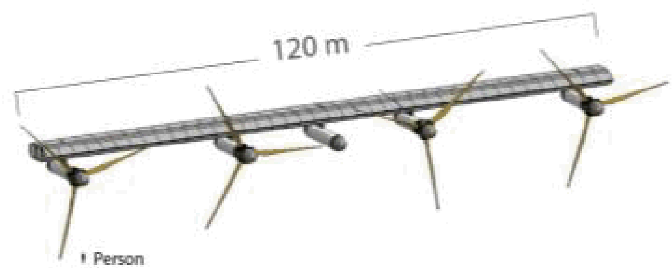
- 3 Current Energy Converters (CECs)
  - RM1 – Dual Rotor Axial Flow Tidal Turbine
  - RM2 – Dual Rotor Cross Flow River Turbine
  - RM4 - 4 Rotor Axial Flow Ocean Turbine

RM1

Tidal Current Turbine

RM2

River Current Turbine



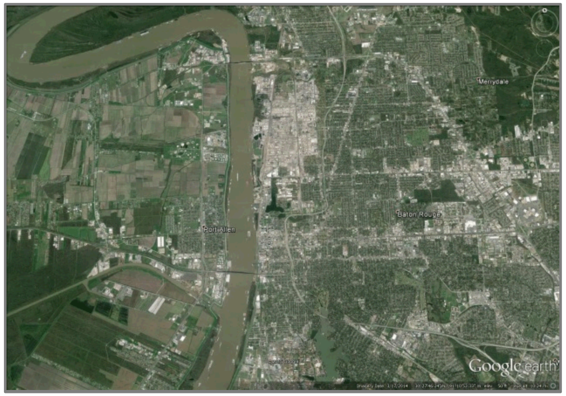
RM4

Ocean Current Turbine

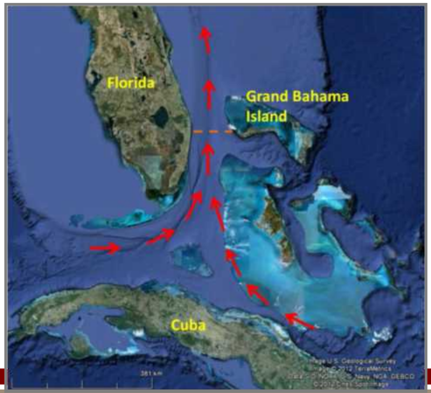
CEC Design and Resource

- RM1
  - Tacoma Narrows – Puget Sound, WA
  - 1.1 MW Rated Power
  - 30% Capacity Factor
- RM2
  - Mississippi River – Baton Rouge, LA
  - 90 kW Rated power
  - 30% Capacity Factor
- RM4
  - Florida Strait – Boca Raton, FL
  - 4 MW Rated Power
  - 70% Capacity Factor

Tacoma Narrows:
Image courtesy of Google Earth



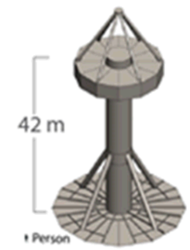
Mississippi River:
Image courtesy of Google Earth

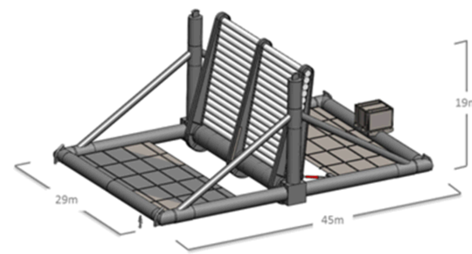


Florida Strait:
Image courtesy of Google Earth

RM Wave Energy Converters

- 3 Wave Energy Converters (WECs)
  - RM3 – Point Absorber
  - RM5 – Oscillating Wave Surge Converter (OWSC)
  - RM6 – Backward Bent Duct Buoy Oscillating Water Column (BBDB)



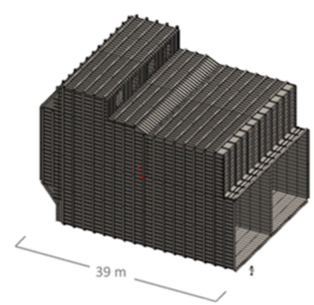


RM3

Wave Point Absorber

RM5

Oscillating Surge Flap

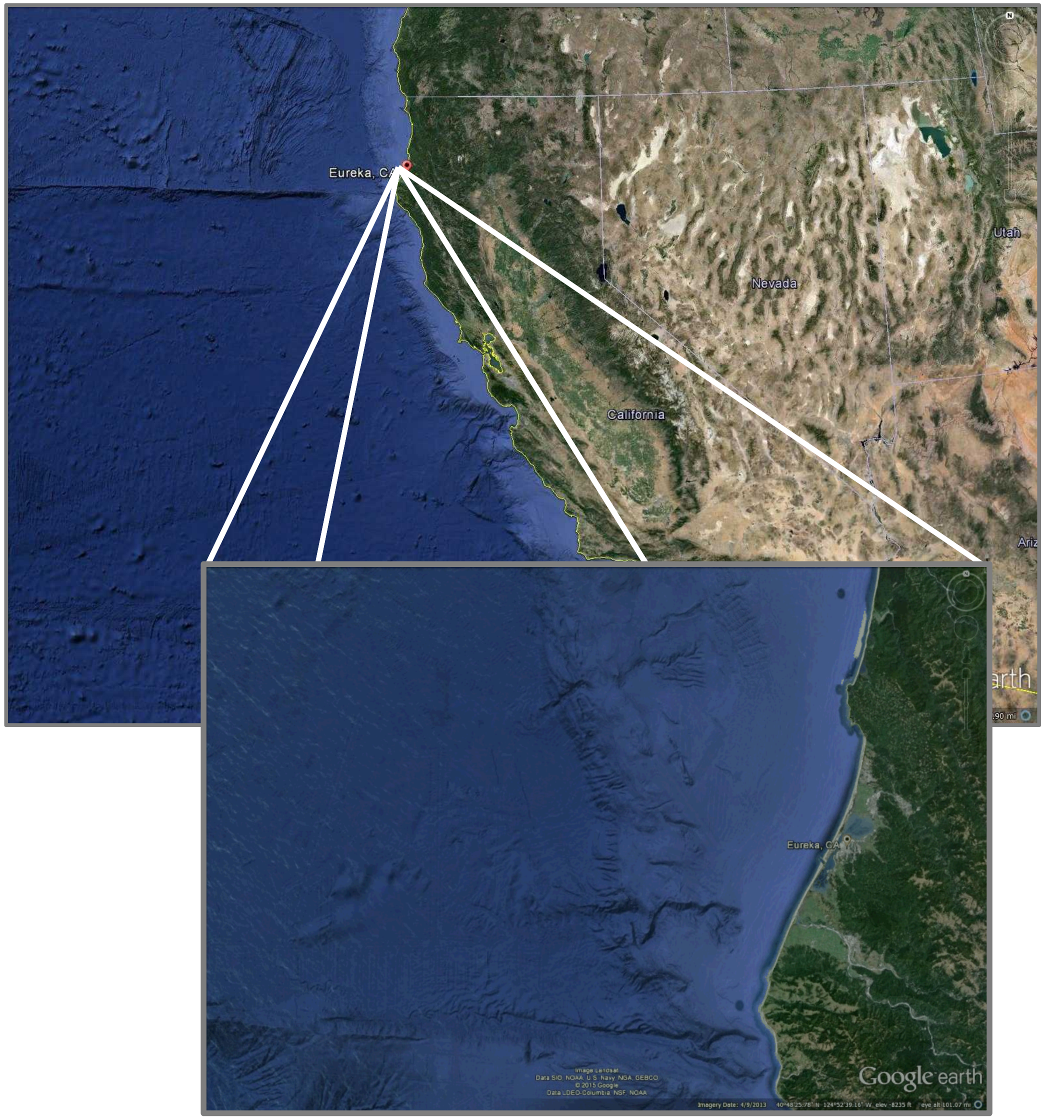


RM6

Oscillating Water Column

WEC Design and Resource

- All WECs designed for Humboldt Bay – Humboldt County, CA
- RM3
  - 286 kW Rated Power
  - 30% Capacity Factor
- RM5
  - 360 kW Rated power
  - 30% Capacity Factor
- RM6
  - 370 kW Rated Power
  - 30% Capacity Factor



Humboldt Bay, near Eureka, CA: Image courtesy of Google Earth