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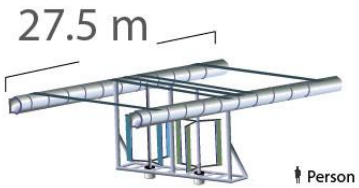

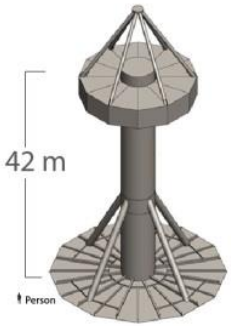

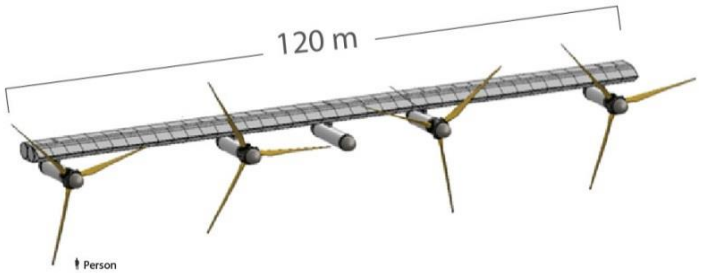

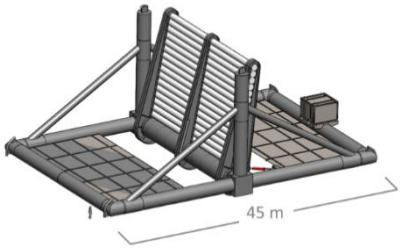

9/2/2016

LEVELIZED COST OF ENERGY FOR MARINE ENERGY CONVERSION (MEC) TECHNOLOGIES

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D. Scott Jenne, Yi-Hsiang Yu (NREL)

EPRC[6], Santa Fe, NM, September 8-9, 2016

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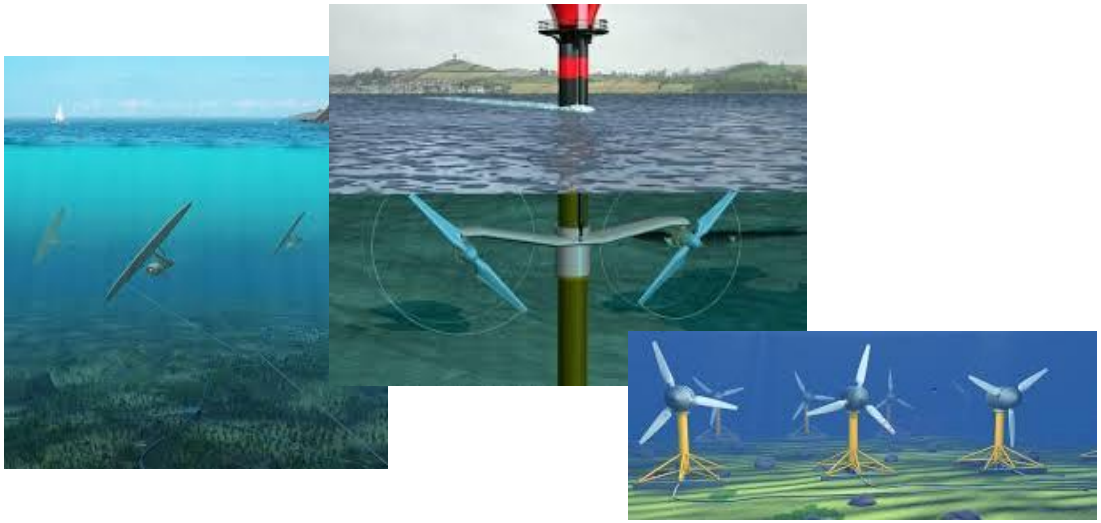
Outline

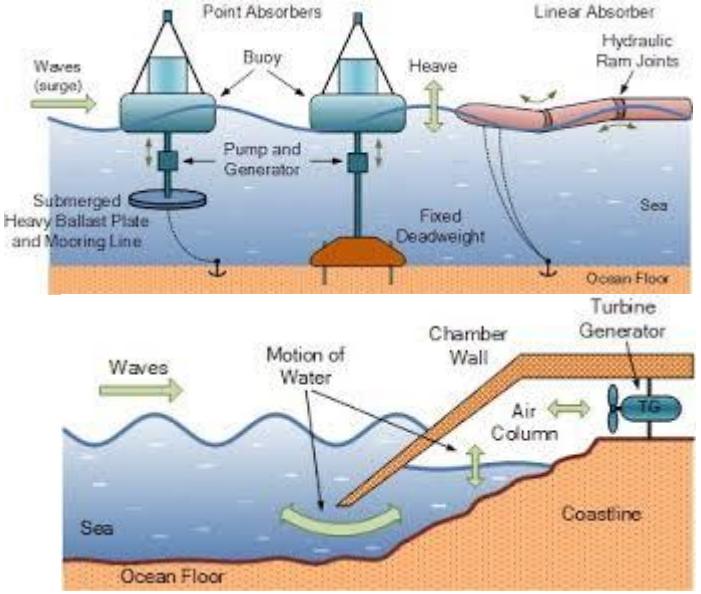
- Reference Model Project
  - Motivation
  - Objectives
  - Designs
- Methodology
- Results
- Conclusions

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 cost reduction opportunities
    - Identify information gaps



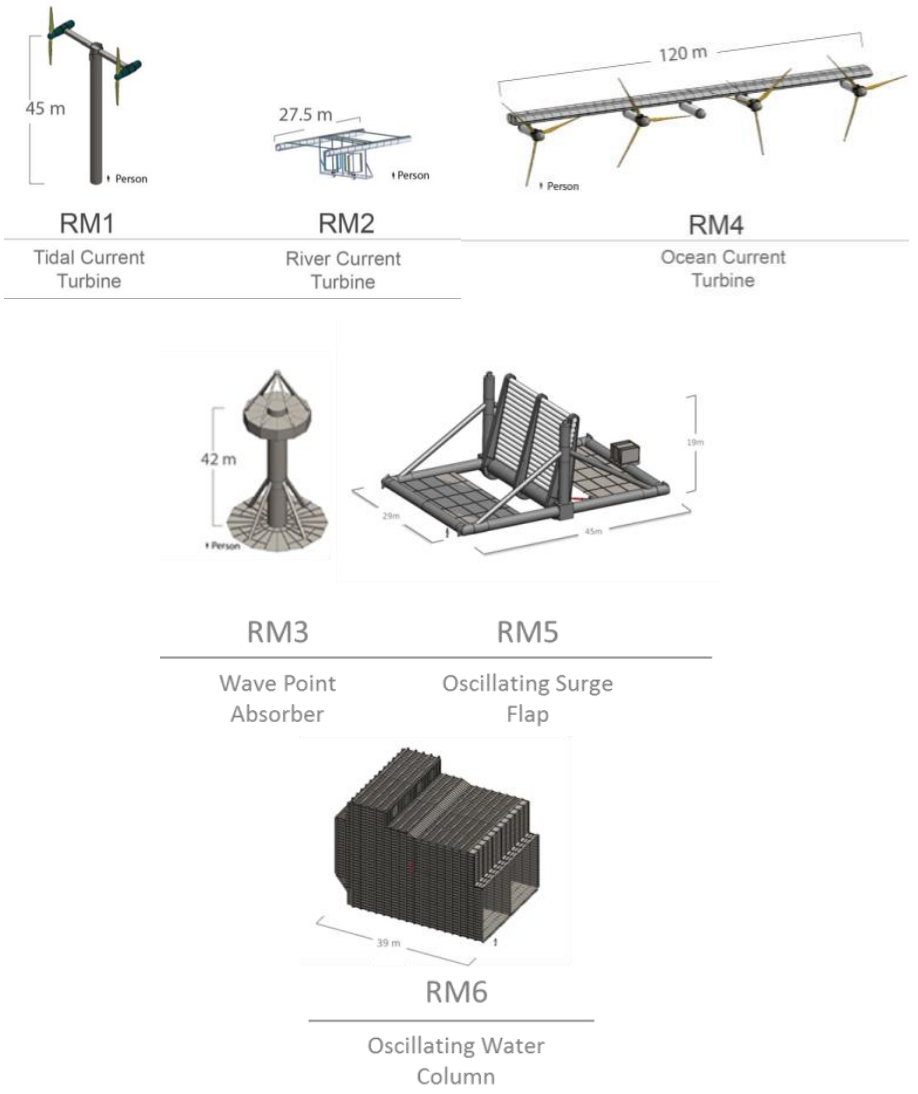
current energy converters (CEC)



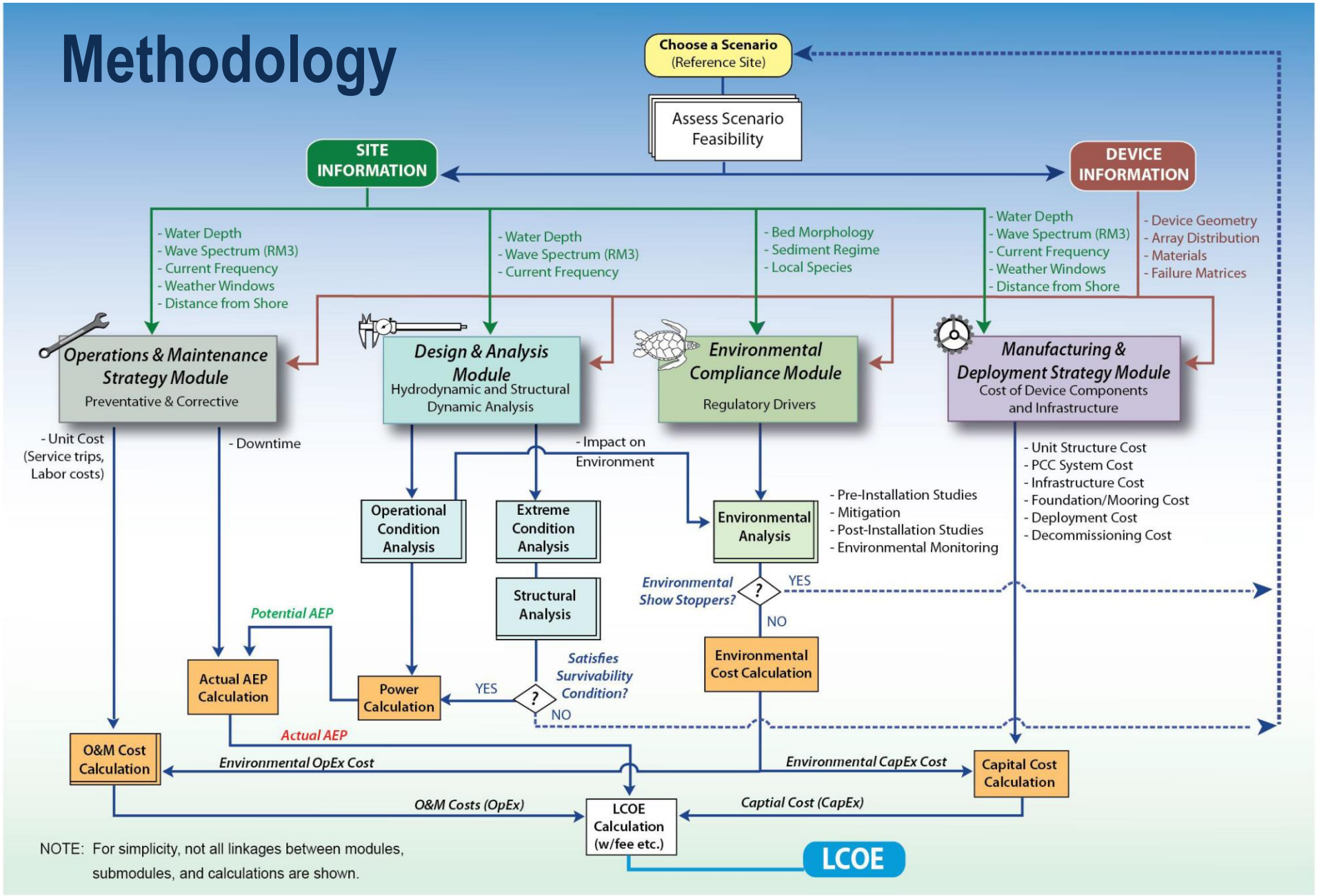
wave energy converters (WEC)

Reference Models

- Non-Proprietary Devices
  - 3 generic Current Energy Converters (CECs)
  - 3 generic Wave Energy Converters (WECs)
- Point Designs
  - Reference resource site
  - Utilizing “today’s” technology
    - No Advanced materials, control strategies, etc.
  - 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)
    - Lumped financing term which includes discount rate, inflation, taxes, depreciation, and project life.
    - 10.8% for all RM LCOE calculations

- 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 (may be seen as Power Conversion Chain)
- Subsystem Integration & Profit Margin
- Installation
- Contingency

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

LCOE Formula (OpEx Categories)

- Insurance
- Post Installation Environmental
- Marine Operations
- Shore-side Operations
- Replacement Parts
- Consumables

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

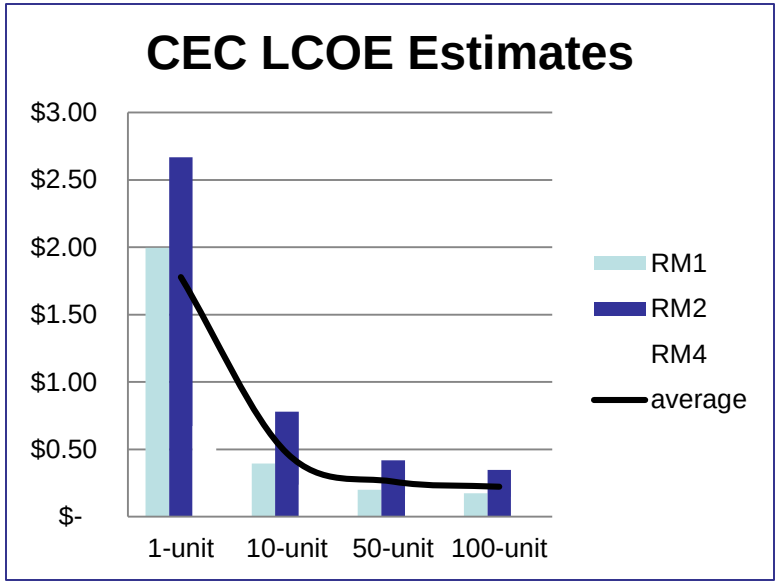
Results - LCOE Overview

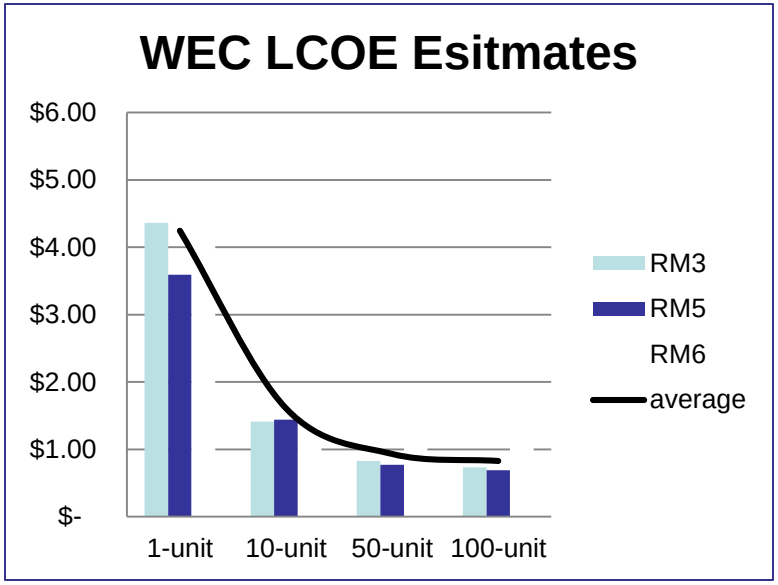
- CECs

	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

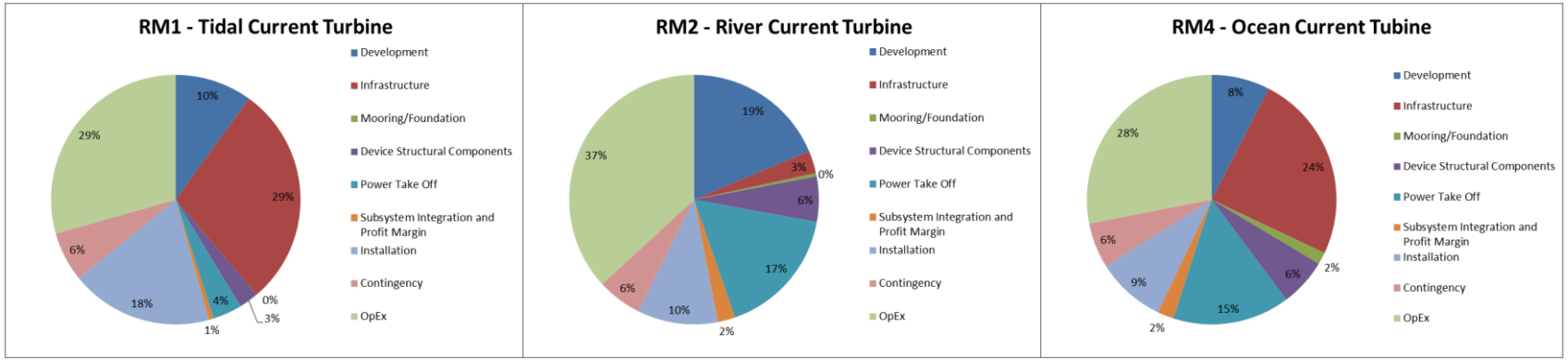
	1	10	50	100
RM3	$ 4.36	$ 1.41	$ 0.83	$ 0.73
RM5	$ 3.59	$ 1.44	$ 0.77	$ 0.69
RM6	$ 4.79	$ 1.98	$ 1.20	$ 1.06
average	$ 4.25	$ 1.61	$ 0.93	$ 0.83



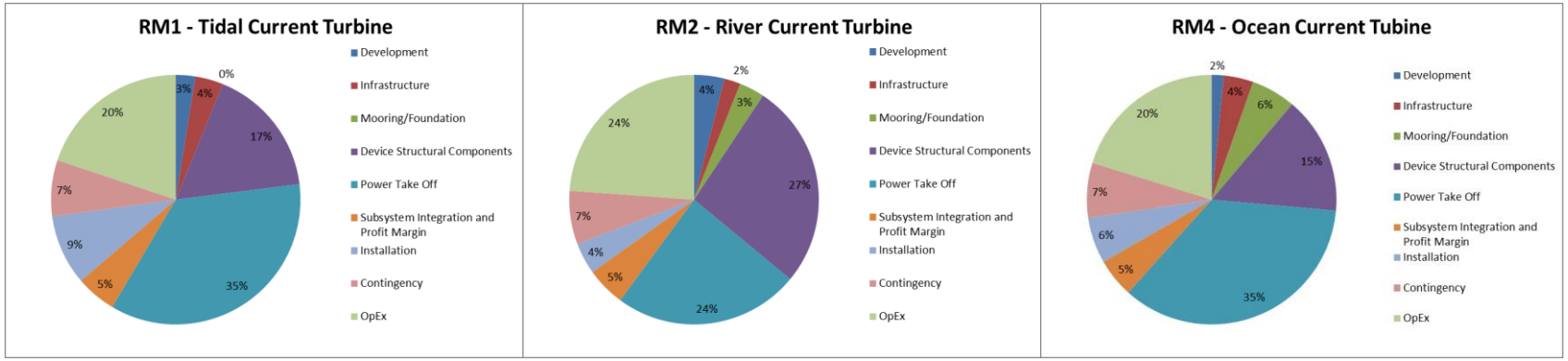


Results – CEC Breakdown

- 1-unit
  - O&M & Infrastructure dominate ocean LCOE
  - O&M, Development & PTO dominate river LCOE

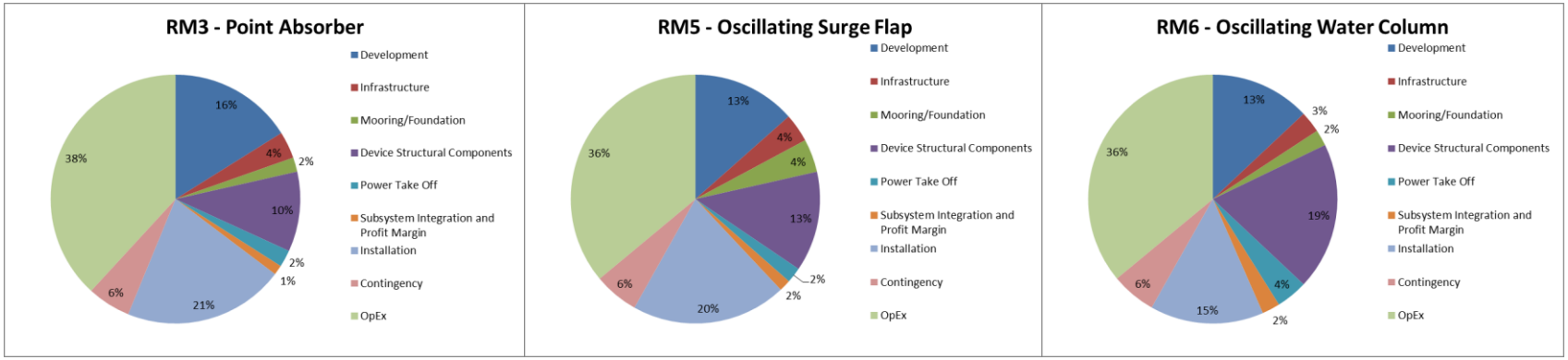


- 100-unit
  - PTO, Structure, and O&M dominate LCOE

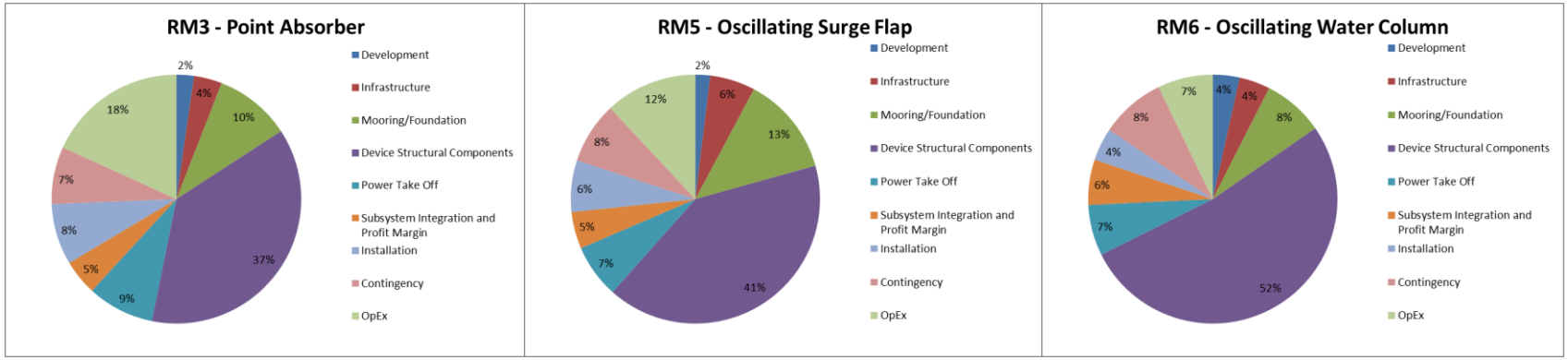


Results – WEC Breakdown

- 1-unit
  - O&M, Development, and Installation are LCOE drivers

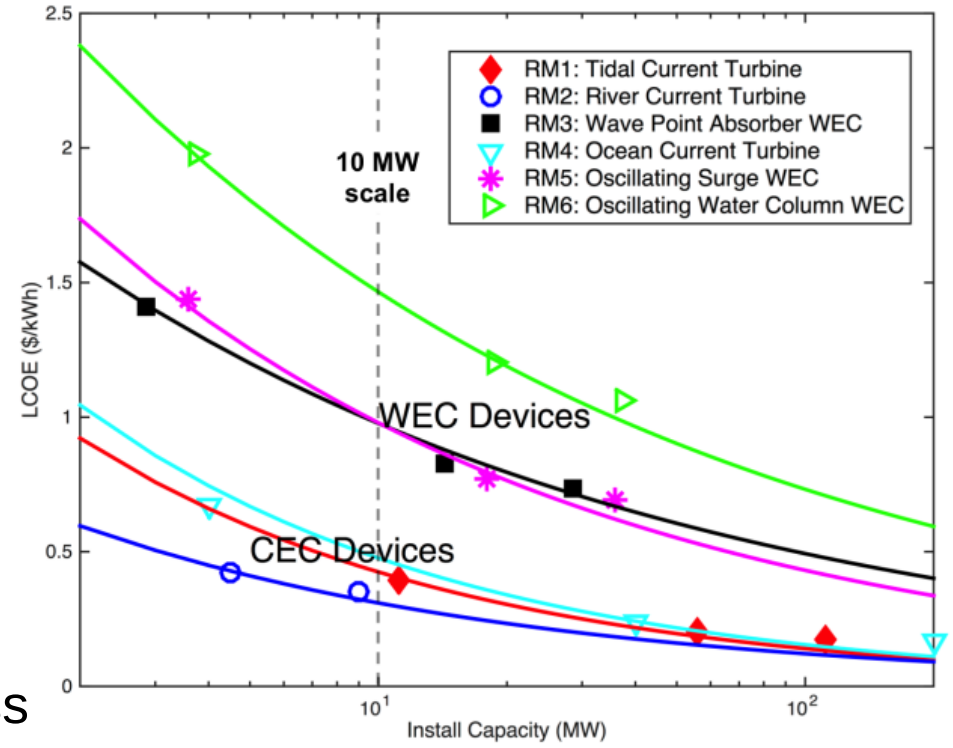


- 100-unit
  - Structure is primary cost driver, which is driven by large structural mass



Results – 10 MW Installed Capacity

- Adjusting for 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.



Conclusions

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Current Energy Converters

- Closer to market readiness
  - Average 100-unit array LCOE ≈ $0.22/kWh
- Largest Potential Reduction Pathways
  - PTO
  - O&M
  - Structure

Wave Energy Converters

- Farther from market readiness
- Large reduction potential
  - Average 100-unit array (approximately 30 MW) LCOE ≈ $0.83/kWh
- Largest Potential Reduction Pathways
  - Structure
  - Mooring (floating designs)
  - O&M
  - Disruptive improvement in performance through advanced controls

ACKNOWLEDGEMENTS:

The project presented were supported by the Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Wind and Water Power Technologies Office (WWPTO). Sandia National Laboratories is a multi-program 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.

Thank you – Questions?

Contact: vsneary@sandia.gov

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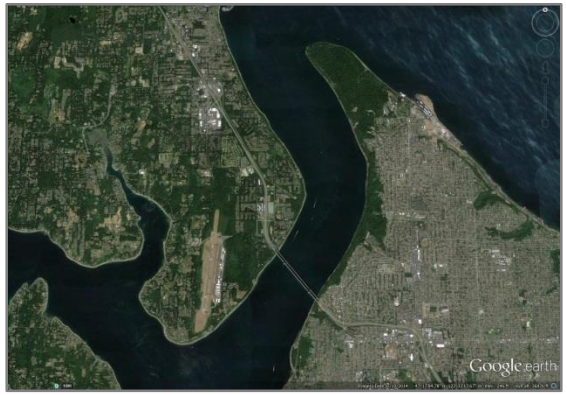
EXTRA SLIDES

RM Current Energy Converters

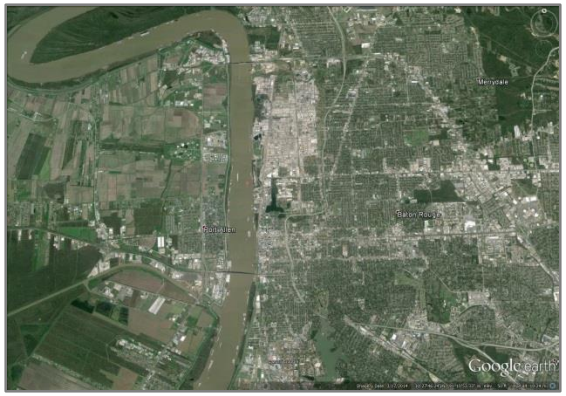
- 3 Current Energy Converters (CECs)
  - RM1 – Dual Rotor Axial Flow Tidal Turbine
  - RM2 – Dual Rotor Cross Flow River Turbine
  - RM4 - 4 Rotor Axial Flow Ocean Turbine

CEC Design and Resource

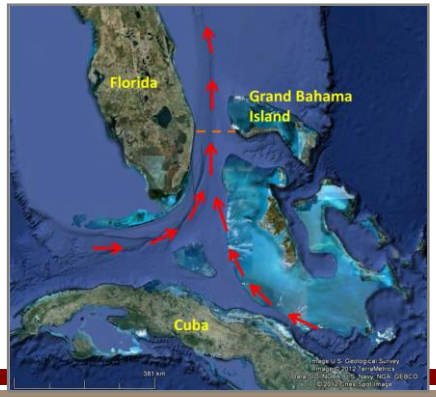
- RM1
  - Tacoma Narrows – Puget Sound, WA
  - 1.1 MW Rated Power
  - 30% Capacity Factor
- RM2
  - Mississippi River – Baton Rouge, LA
  - 90 kW Rated power
  - 30% Capacity Factor
- RM4
  - Florida Strait – Boca Raton, FL
  - 4 MW Rated Power
  - 70% Capacity Factor



Tacoma Narrows:
Image courtesy of Google Earth



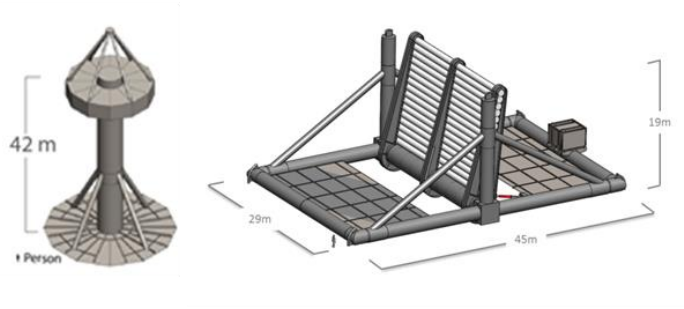
Mississippi River:
Image courtesy of Google Earth



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)

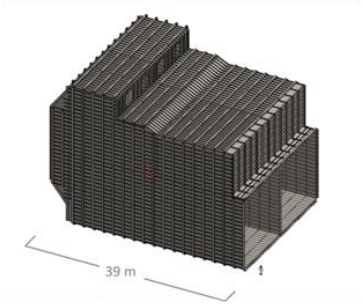


RM3

Wave Point Absorber

RM5

Oscillating Surge Flap

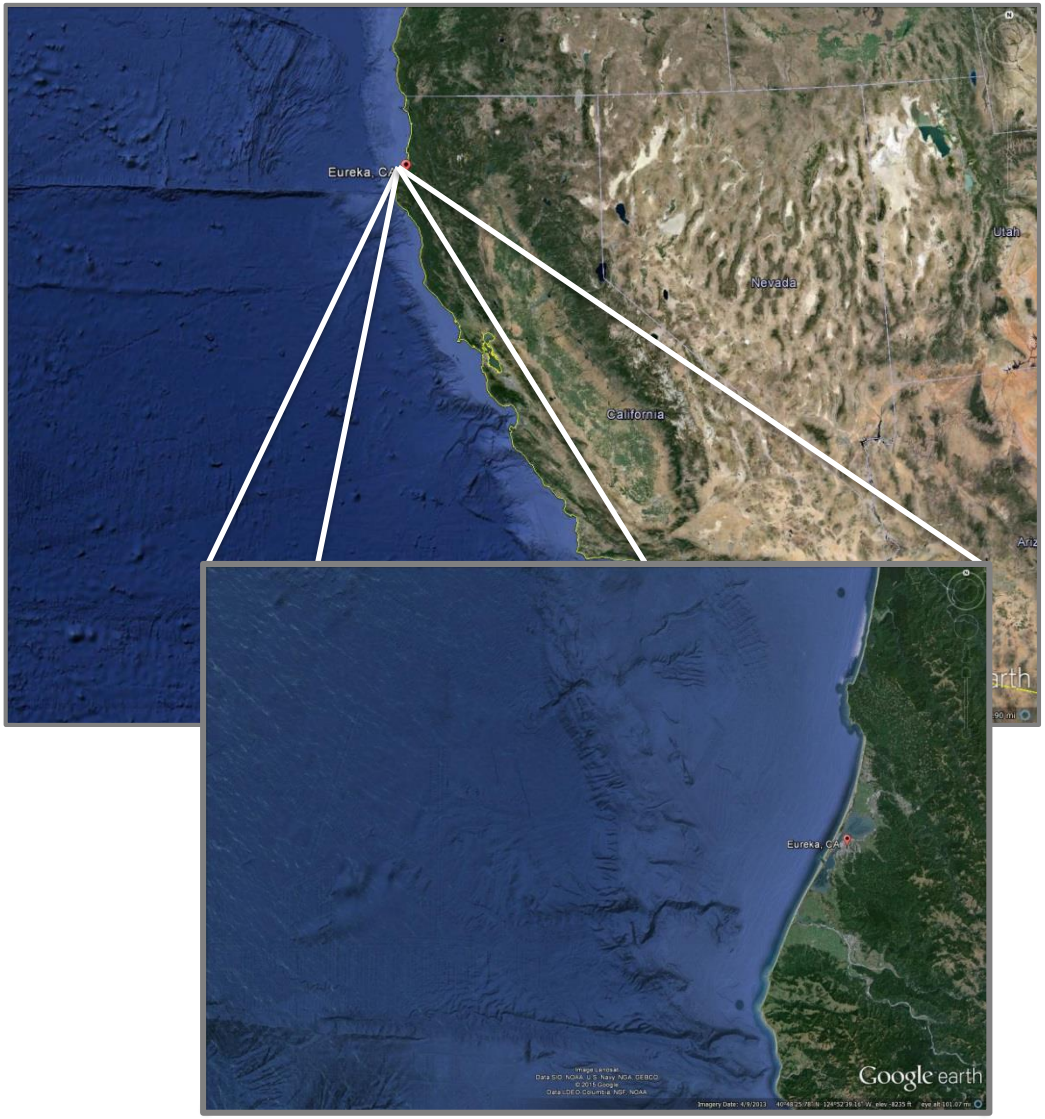


RM6

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