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
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**
- **Performance Modeling**
- **Columbia Power 1/15th Scale Test (OSU)**
- **Coupled Device Array and Environmental Analysis**

**Materials & Coatings**
- Cavitation

**Hydro-Acoustics**
- Rotor Design & Testing
- Power Takeoff Testing

**Technology Development Cycle**
- Components
- Sub-systems
- System Testing
- Deployment

- **SNL EFDC**
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
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

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

\[
LCOE = \frac{(FCR \times \text{CapEx}) + \text{OpEx}}{\text{AEP}}
\]
Results - LCOE Overview

- **CECs**

<table>
<thead>
<tr>
<th></th>
<th>1-unit</th>
<th>10-unit</th>
<th>50-unit</th>
<th>100-unit</th>
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<tbody>
<tr>
<td>RM1</td>
<td>$1.99</td>
<td>$0.40</td>
<td>$0.20</td>
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<td>RM2</td>
<td>$2.67</td>
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<td>$0.42</td>
<td>$0.35</td>
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<td>$0.67</td>
<td>$0.24</td>
<td>$0.17</td>
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<tr>
<td>average</td>
<td>$1.78</td>
<td>$0.47</td>
<td>$0.26</td>
<td>$0.22</td>
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- **WECs**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>10</th>
<th>50</th>
<th>100</th>
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<tr>
<td>RM3</td>
<td>$4.36</td>
<td>$1.41</td>
<td>$0.83</td>
<td>$0.73</td>
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<tr>
<td>RM5</td>
<td>$3.59</td>
<td>$1.44</td>
<td>$0.77</td>
<td>$0.69</td>
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<tr>
<td>RM6</td>
<td>$4.79</td>
<td>$1.98</td>
<td>$1.20</td>
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<td>average</td>
<td>$4.25</td>
<td>$1.61</td>
<td>$0.93</td>
<td>$0.83</td>
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**CEC LCOE ESTIMATES**

**WEC LCOE ESTIMATES**
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
Summary of results

Power increase of >330%

<table>
<thead>
<tr>
<th></th>
<th>Resistive</th>
<th>CCC</th>
<th>Latching</th>
<th>LQG</th>
<th>PDC3</th>
<th>Linear MPC</th>
<th>DP</th>
<th>SB</th>
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<tr>
<td>Average power-in</td>
<td>0</td>
<td>279</td>
<td>0</td>
<td>46.5</td>
<td>45.8</td>
<td>98.8</td>
<td>374.8</td>
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<td>Average power-net</td>
<td>15.5</td>
<td>52.5</td>
<td>28.8</td>
<td>39.8</td>
<td>25.5</td>
<td>46.1</td>
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<td>Average energy-stored</td>
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<td>251</td>
<td>0</td>
<td>27.5</td>
<td>42.9</td>
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<td>Power-in, peak/RMS</td>
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<td>5.8</td>
<td>0.0</td>
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<td>5.1</td>
<td>5.6</td>
<td>5.4</td>
<td>4.3</td>
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<td>Power-net, peak/RMS</td>
<td>7.3</td>
<td>38.8</td>
<td>6.2</td>
<td>14.3</td>
<td>17.3</td>
<td>20.2</td>
<td>60.1</td>
<td>16.2</td>
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<td>Total absolute power flow</td>
<td>15.5</td>
<td>313.3</td>
<td>28.8</td>
<td>76.0</td>
<td>91.5</td>
<td>131.8</td>
<td>384.9</td>
<td>54.5</td>
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PCC requirements

<table>
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<td>Slew rate requirements</td>
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<td>1.5E+6</td>
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<tr>
<td>PCC force, RMS</td>
<td>315</td>
<td>2367</td>
<td>923</td>
<td>915</td>
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<td>PCC Force, peak/RMS</td>
<td>2.35</td>
<td>1.82</td>
<td>2.27</td>
<td>2.15</td>
<td>1.71</td>
<td>1.89</td>
<td>2.14</td>
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Mechanical loading

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<th>Oscillation amplitude, peak</th>
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<td></td>
<td>0.06</td>
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<td>Oscillation amplitude, peak/RMS</td>
<td>2.52</td>
<td>1.97</td>
<td>2.05</td>
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<td>1.89</td>
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<td>Oscillation velocity, peak</td>
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<td></td>
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<td>0.30</td>
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<td>0.50</td>
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<tr>
<td>Oscillation velocity, peak/RMS</td>
<td>2.63</td>
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<td>2.77</td>
<td>2.43</td>
<td>2.30</td>
<td>2.33</td>
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<tr>
<td>Oscillation acceleration, peak</td>
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<td>CCC</td>
<td>Latching</td>
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<td></td>
<td>0.39</td>
<td>1.02</td>
<td>0.45</td>
<td>0.78</td>
<td>0.22</td>
<td>0.46</td>
<td>1.27</td>
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<tr>
<td>Oscillation acceleration, peak/RMS</td>
<td>2.70</td>
<td>2.39</td>
<td>1.21</td>
<td>2.58</td>
<td>2.30</td>
<td>1.95</td>
<td>2.36</td>
<td>2.56</td>
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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).

**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)

MHK Composite Performance

Uni. of New Hampshire

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

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

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.
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
- 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

Location
- United States: 73
- Germany: 5
- China: 6
- India: 5
- United Kingdom: 10
- South Korea: 10
- Italy: 1
- Other: 53

Industry
- Wind: 96
- Water: 1
- Other: 20
- Aerospace: 5
- Military: 64

Organization Type
- School: 87
- Laboratory: 5
- Consultant: 20
- Manufacturer: 34
- Other: 22
- Individual: 18

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

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- 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

THANK YOU
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
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)
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