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

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Introduction

The U.S. Department of Energy (DOE) estimates that the theoretical average annual energy available from ocean waves and currents is approximately 1,445 TWh/year, approximately one-third of the nation's total annual electricity usage. Although this estimate represents the theoretical upper bound of our nation's marine energy resource, extracting just a small fraction of it by developing efficient and cost-competitive marine energy conversion (MEC)[2] technologies could contribute significantly to the U.S. renewable energy portfolio and to efforts reducing carbon emissions. Further, most of this potential energy resource is close to large coastal population centers.

Determining how DOE can best support research and development (R&D) for MEC technologies requires the application of common performance metrics derived using uniform methodologies in order to benchmark a given technology's performance and measure improvements to performance as it advances its technology performance level (TPL) and technology readiness level (TRL). This uniform assessment methodology is especially important given the diversity of MEC technologies being proposed. MEC technologies include current energy converters (CEC), which generate electricity from the hydrokinetic energy of moving water currents, and wave energy converters (WEC), which generate electricity from the hydrokinetic energy in waves. There are a multitude of CEC and WEC archetypes and deployment strategies. Unlike land-based wind energy, which converged on the three-bladed horizontal axis wind turbine (HAWT), there is no clear leading technology in marine energy to focus R&D efforts. CECs are predominantly analogues of HAWTs and vertical axis wind turbines (VAWT), and resources include river, tidal and ocean currents. WECs, generally have relatively lower TPLs and TRLs, and are more varied in their maturity, scale, and design.

The DOE's reference model project (RMP) was a multi-year effort to develop and apply a uniform assessment methodology to benchmark the performance of MEC technologies. As part of this effort, a half dozen MEC technologies were designed to serve as reference models (RM). These RMs, paired with reference resource sites, allowed calculation of the Levelized Cost of Energy (LCOE) for single units to multiple-unit projects and a detailed cost breakdown structure to identify cost-drivers and to develop cost-reduction pathways as detailed in Neary et al. (2014a,b), Yu et al. (2015) and Bull et al. (2014). Data from the RMP was used to benchmark LCOE for small commercial scale MEC arrays of 10 MW installed capacity, as detailed by Jenne et al. (2015). The economic results from the RMP studies are reviewed herein.

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[2] We adopt the term Marine Energy Conversion (MEC) throughout this document in place of Marine Hydrokinetic (MHK).

Reference Models

The reference models in the RMP study are coupled point designs of MEC technologies, spanning individual units up to 100-unit projects, with reference resource sites. The CEC and WEC units are shown in
Figure 1 and Figure 2, and are summarized as follows:

- **RM1:** A dual-rotor, axial flow tidal turbine (horizontal axis) designed to extract energy from tidal currents modeled after the Tacoma Narrows in Puget Sound, Washington, with a capacity factor estimated at 0.3, and an installed capacity per unit is 1 MW.
- **RM2:** A dual-rotor, cross flow river turbine designed to extract energy from river currents modeled after a section of the lower Mississippi river near Baton Rouge, Louisiana, with a capacity factor estimated at 0.3, and an installed capacity per unit is 0.2 MW.
- **RM3:** A two body floating-point absorber designed to capture energy from a wave site near Eureka, in Humboldt County California, with a capacity factor estimated at 0.3, and an installed capacity per unit is 0.3 MW.
- **RM4:** A moored glider with four axial flow turbines designed to extract energy from ocean currents modeled after the Florida Strait within the Gulf Stream off of the Southeast coast of Florida near Boca Raton, with a capacity factor estimated at 0.7, and an installed capacity per unit is 4 MW.
- **RM5:** A floating oscillating surge wave energy converter designed to capture energy from a wave site near Eureka, in Humboldt County California, with a capacity factor estimated at 0.3, and an installed capacity per unit is 0.36 MW.
- **RM6:** A floating Backwards Bent Duct Buoy (BBDB) Oscillating Water Column (OWC) designed to capture energy from a wave site near Eureka, in Humboldt County California, with a capacity factor estimated at 0.3, and an installed capacity per unit is 0.2 MW.

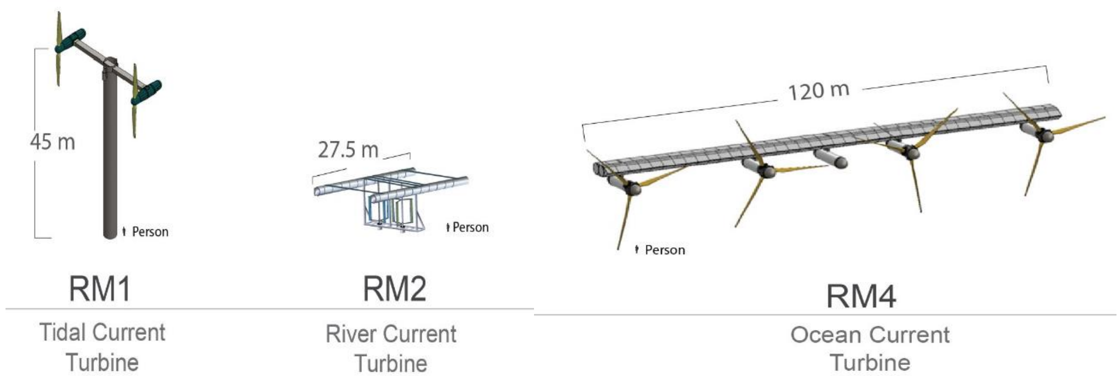

FIGURE 1. SCHEMATIC OF CECS (RM1, RM2, RM4)

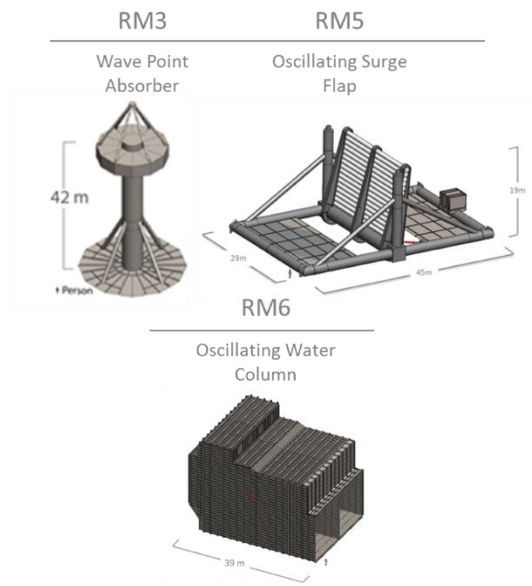

FIGURE 2. SCHEMATIC OF WECS (RM3, RM5, RM6)

Methodology

The methodology for design, analysis, and LCOE estimation for MEC technologies is illustrated in Figure 3. It centers on four core modules (operation & maintenance, design & analysis, environmental compliance, and manufacturing and deployment strategy), and includes iterations needed to meet key constraints imposed for structural design and for environmental compliance. A summary of this methodology is provided by Neary et al. (2014a,b).

LCOE is calculated using the following expression

$$\mathrm{LCOE} = \frac{(\mathrm{FCR} \times \mathrm{ICC}) + \mathrm{O\&M}}{\mathrm{AEP}}$$

Independent variables in this expression include the initial capital cost (ICC) and annual operating and maintenance cost (O&M), the annual energy production (AEP), representing grid-tied electricity, and the fixed charge rate (FCR). The FCR equates to the annual return that is needed to meet investor requirements. Included in the FCR are the real discount rate, inflation, tax rates, depreciation and project life.

LCOE, described by the Energy Information Administration (EIA), as “a measure of the overall competiveness of different generating technologies,” is the level of sales revenue per kilowatt-hour (kWh) of grid-tied electricity production needed for an electricity-generating venture to “break even” in the sense that the project covers all capital and operating expenses and satisfies a minimum rate of return for investors over the project’s lifetime. It is a common performance metric that normalizes the cost of a marine energy project, whether it be a single device or multiple devices in a farm, with the amount of grid-tied electricity it can generate.

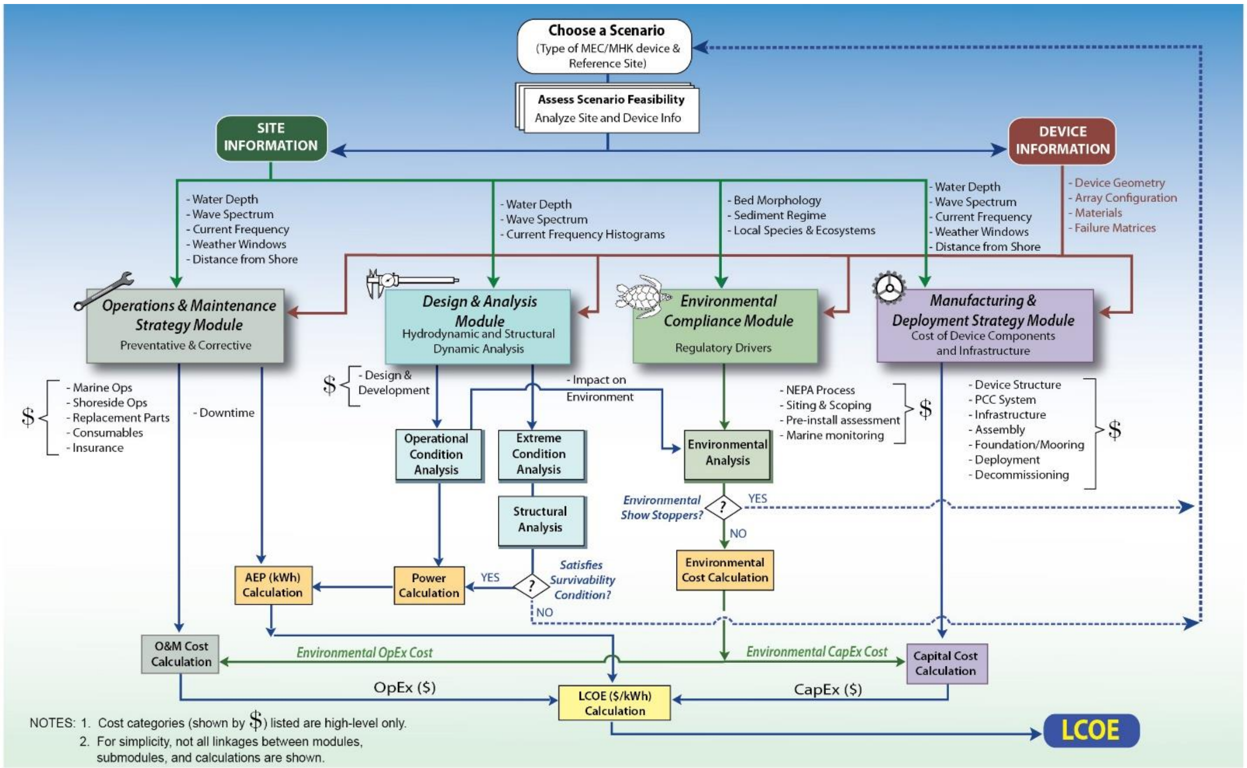

Figure 3. Methodology for design, analysis, and LCOE estimation for MEC technologies (Neary et al. 2014a,b).

Details on the standardized cost breakdown structure used for estimating the LCOE are given in LaBonte et al. (2013). Annualized costs include all capital and operational expenditures (CapEx and OpEx) normalized by the estimated annual energy production (AEP) in kWh. In the RMP studies, ICC and O&M costs are delineated into the categories shown in TABLE 1. These categories are subdivided further into subcategories depending on the RM design.

TABLE 1. COST CATEGORIES FOR ICC AND O&M

ICC	O&M
Development	Insurance
Infrastructure	Post installation environmental
Mooring/foundation	Marine operations
Device structural components	Shore-side operations
Power Take Off (PTO)	Replacement parts
Subsystem integration & profit margin	Consumables
Installation	-
Contingency	-

Results

Values for LCOE are summarized in TABLE 2, for CECs, and TABLE 3, for WECs. LCOE reduces exponentially as the number of units and installed capacity of project increases. As noted in Neary et al. (2014b), the LCOE for the tidal current turbine RM1 ($0.40/kWh) is roughly double the LCOE estimated for offshore wind turbines ($0.20/kWh[3]). The low LCOE for the ocean current turbine RM4 ($0.24/kWh) is due to the high installed capacity for each device (4 MW) and the high capacity factor (CF=0.7) due to the constancy of the Gulf Current in the Florida Strait. For the river current turbine RM2, the high LCOE ($0.78/kWh) is due to the low installed capacity factor and the spatial constraints inherent at a river site. The LCOE estimate for the WEC devices RM3, RM5 and RM6 are significantly higher by comparison, but this largely reflects the lack of experience and tools available for designing this technology at the time of the RMP studies. Unlike the turbine-based current energy conversion (CEC) RM designs, which benefited from decades of DOE laboratory R&D experience and investment in wind turbine technologies, there was relatively little design experience and modeling tools that could be leveraged to design WEC devices. Critical innovations to improve performance of WECs, such as advanced controls, were also not applied.

One of the goals of the RMP studies was to identify key cost drivers to help focus future R&D efforts. For all CEC RMs (RM1, RM2, and RM4), CapEx contributions (development, M&D, subsystem integration, profit margin, and contingency) are much greater than OpEx contributions—with M&D dominating the CapEx contributions to their LCOEs. The cost for environmental studies and permitting activities, which are captured in the project development cost contributions to LCOE, are insignificant by comparison. However, environmental costs have medium to high uncertainty and will be case dependent. Structural components and the power-take-off (PTO) are clear cost drivers for all of the RMs and device components for which future R&D efforts should be methodically applied to reduce costs and LCOE. For the WEC RMs (RM3, RM5, and RM6) the mooring system and its installation are also key cost drivers. Future R&D efforts should also focus on increasing WEC device performance and the resulting AEP, which will lower the LCOE as well.

TABLE 2. CEC LCOE AT SINGLE-UNIT, AND MULTI-UNIT ARRAYS (BASED ON JENNE ET AL. 2015)

	1-unit	**10-unit**	**50-unit ($/kWh)**	**100-unit**	**10 MW**
RM1	1.99	0.40	0.20	0.17	0.42
RM2	2.67	0.78	0.42	0.35	0.31
RM4	0.67	0.24	0.17	0.15	0.48

TABLE 3. LCOE AT SINGLE-UNIT, AND MULTI-UNIT ARRAYS (BASED ON JENNE ET AL. 2015)

	1-unit	**10-unit**	**50-unit ($/kWh)**	**100-unit**	**10 MW**
RM3	4.36	1.41	0.83	0.73	0.98
RM5	3.59	1.44	0.77	0.69	0.98
RM6	4.79	1.98	1.20	1.06	1.47

LCOE estimates for small scale 10 MW projects (TABLES 1 and 2) are extrapolated from LCOE vs. installed capacity curves (Figure 4). CEC projects based on RM1, RM2 and RM4 have fairly similar LCOE

[3] "U.S. Energy Information Administration (EIA) - Source". *www.eia.gov. Retrieved 2015-11-02*

between $0.30 and $0.50/kWh and roughly double the values reported for offshore wind turbines. Those for WECs based on RM3, RM5 and RM6 are significantly greater, between $1.00 and $1.50/kWh.

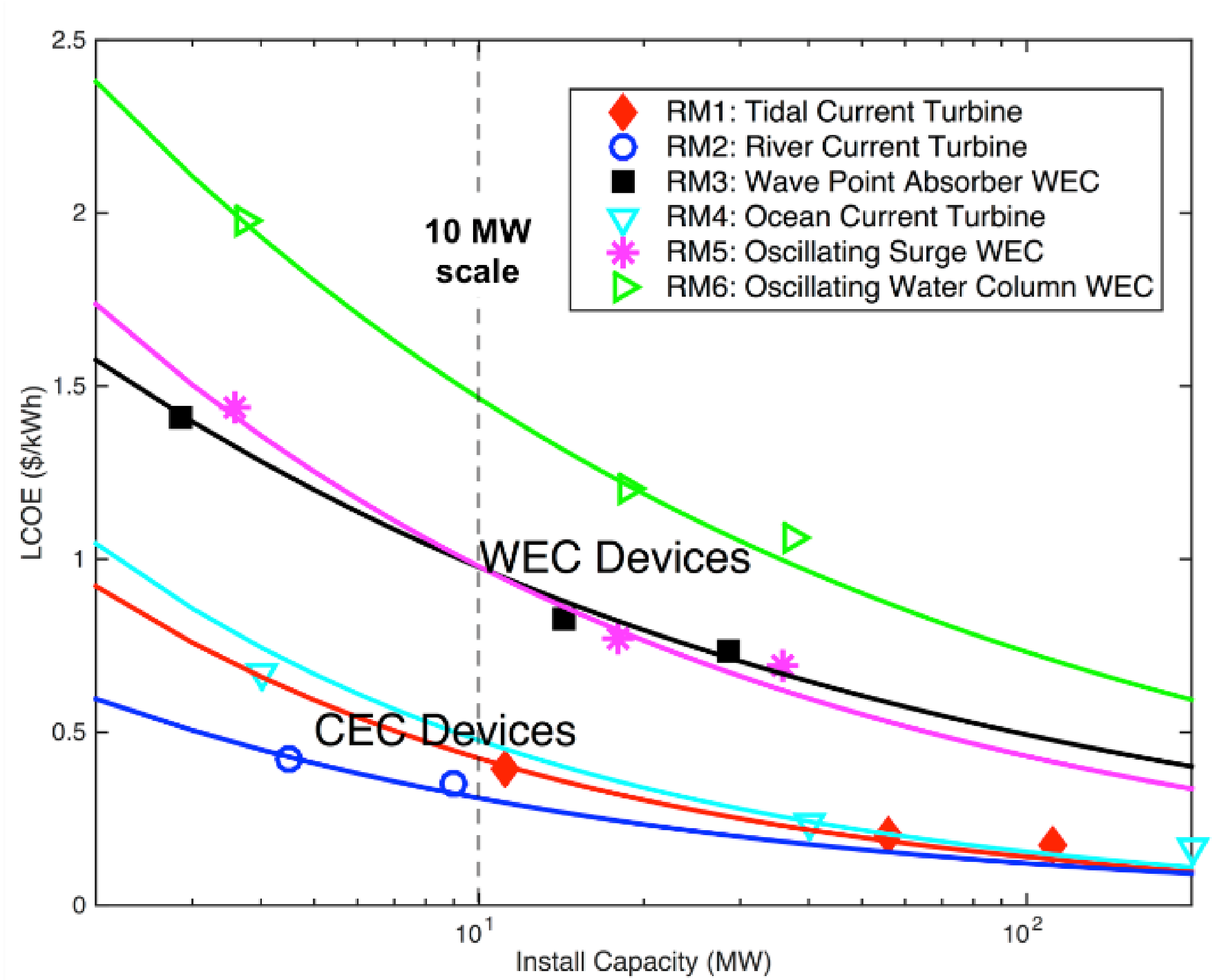

FIGURE 4. LCOE VS. INSTALLED CAPACITY (FROM JENNE ET AL. 2015)

Conclusions

These LCOE estimates are influenced by many factors, including the installed capacity, constancy of the resource (which affects capacity factor), technology readiness level, and AEP and cost uncertainty. In contrast to wave energy converters, relatively lower LCOE for current energy converters (i.e., tidal and ocean current turbines) reflects leveraging of decades of design knowledge and operational experience from wind energy. The RMP studies also informs strategies for cost reduction. Structural costs and costs for power take offs are clear cost drivers for which future R&D efforts should be directed, particularly for WECs. R&D efforts are therefore needed to reduce primary cost drivers or increase annual energy production, e.g., through advanced control strategies.

References

Bull D., Smith C., Jenne D. S., Jacob P., Copping A., Willits S., Fontaine A., Brefort D., Copeland G., Gordon M., Jepsen R., 2014, Reference Model 6: Oscillating Wave Energy Converter, Sandia National Laboratories, Albuquerque, NM.

Jenne, D.S., Yi-Hsiang, Y. and V.S. Neary, 2015, Levelized cost of energy analysis of marine and hydrokinetic reference models. Proceedings of 3rd Annual Marine Energy Technology Symposium 2015 (METS2015), Washington, D.C., April 27-29. (Also available as NREL report: NREL/CP-5000-64013, http://www.nrel.gov/docs/fy15osti/64013.pdf)

LaBonte A., Connor P. O., Fitzpatrick C., Hallett K., Li Y., 2013, "Standardized Cost and Performance Reporting for Marine and Hydrokinetic Technologies," 1st Marine Energy Technology Symposiumt, GMREC/MTES.

Neary V. S., Previsic M., Jepsen R. A., Lawson M. J., Yu Y.-H., Copping A. E., Fontaine A. A., Hallett K. C., Murray D. K., 2014a, Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies, Sandia National Laboratories, Albuquerque, NM

Neary V. S., Previsic M., Jepsen R., Lawson M. J., Yu Y.-H., Copping A. E., Fontaine A., and Hallett K. C., 2014b, Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies, Proceedings of 2nd Marine Energy Technology Symposium 2014 (METS2014), at the 7th Annual Global Marine Renewable Energy Conference (GMREC 2014), Seattle, WA, April 15-18.

Yu Y.-H., Jenne D. S., Thresher R., Copping A., Geerlofs S., Hanna L., 2015, Reference Model 5: Oscillating Surge Wave Energy Converter, National Renewable Energy Laboratory (NREL), Golden, CO.