METHODOLOGY FOR DESIGN AND ECONOMIC ANALYSIS OF MARINE ENERGY CONVERSION (MEC) TECHNOLOGIES

Vincent S. Neary[1]
Sandia National Laboratories
Albuquerque, NM, U.S.A.

Michael Lawson
National Renewable Energy Laboratory
Boulder, CO, U.S.A.

Mirko Previsic
Re Vision Consulting, LLC
Sacramento, CA, U.S.A.

Andrea Copping
Pacific Northwest National Laboratory
Seattle, WA, U.S.A.

Kathleen C. Hallett
National Renewable Energy Laboratory
Boulder, CO, U.S.A

Alison LaBonte
Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, D.C.

Jeff Rieks
Cardinal Engineering, LLC
Annapolis, MD, U.S.A.

Dianne Murray
Sandia National Laboratories
Albuquerque, NM, U.S.A.

[1]Corresponding author: vsneary@sandia.gov

ABSTRACT
This paper presents results of the Reference Model Project (RMP), which began five years ago to facilitate Marine Energy Conversion (MEC) technology development and market acceleration. The four Reference Models presented herein are point designs of common MEC technology archetypes that allowed the benchmarking of technical and economic performance, and the identification of knowledge gaps, cost drivers, and cost reduction pathways that require further research and development. This project generated detailed CAD (SolidWorks) geometry files for each point design along with physical model data sets. In December 2013, Sandia National Laboratories launched a public website at http://energy.sandia.gov/rmp, which serves as a data clearing house for other MEC researchers and developers to access all supporting design documents, SolidWorks geometry files, LCOE estimation spreadsheets, and experimental data sets.

INTRODUCTION
Recent estimates indicate the maximum theoretical annual energy production (AEP) that could be produced from waves and tidal currents is approximately 1,420 TWh per year, approximately one-third of the nation's total annual electricity usage (Hagerman et al. 2011, Haas et al. 2011). This finding has renewed government and commercial interest in Marine Energy Conversion (MEC)[1] technologies and indicates that wave and tidal energy could play a significant role in the U.S. renewable energy portfolio in the years to come. However, MEC technologies are at a nascent stage of development and require significant research and development (R&D) before becoming cost-competitive with other energy generation technologies on a commercial scale. In response to this need, the U.S. Department of Energy (DOE) initiated the Reference Model Project (RMP) to develop nonproprietary open-source Reference Model (RM) point designs of common MEC technology archetypes for public dissemination; point designs are unique devices designed for reference marine energy resource sites modeled after actual sites.

Specific RMP study objectives included:

1) Develop a methodology for design and economic analysis of MEC technologies;

2) Apply this methodology to design and analyze *open-source* reference model (RM) devices and arrays for MEC archetypes paired with reference marine energy resource sites—meaning the RM devices are unique point designs and are not intended

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

to be generic or average representations of MEC archetypes;

3) Apply this methodology to estimate levelized costs of energy (LCOE) in dollars per kilowatt hour ($/kWh) for each RM point design/resource pair, where LCOE is defined as the total annualized cost of the technology (including all Capital and Operational expenditures [CapEx and OpEx]) normalized by the estimated annual energy production (AEP) in kWh.

Four RM point design/resource pairs, illustrated in Figure 1, were developed to serve as 'study objects' for technical and economic assessment:

RM1—A dual-rotor axial-flow (horizontal-axis) tidal turbine designed for a reference tidal current energy resource modeled after the Tacoma Narrows in Puget Sound, Washington.

RM2—A dual-rotor vertical-axis cross-flow river turbine designed for a reference river current energy resource modeled after a reach in the lower Mississippi River near Baton Rouge, Louisiana.

RM3—A wave point absorber designed for a reference wave energy resource modeled after a wave site near Eureka, in Humboldt County California.

RM4—A moored glider with four axial-flow ocean current turbines designed for a reference ocean current energy resource modeled after the Florida Strait ocean current site, within the Gulf Stream off the southeast coast of Florida near Boca Raton.

The reference resource sites listed above were modeled after actual tidal, river, ocean current energy, and wave energy sites that industry and the R&D community[2] can use to design and evaluate their own MEC technologies and levelized cost of energy (LCOE) estimates.

RM1 — Tidal Current Turbine

RM2 — River Current Turbine

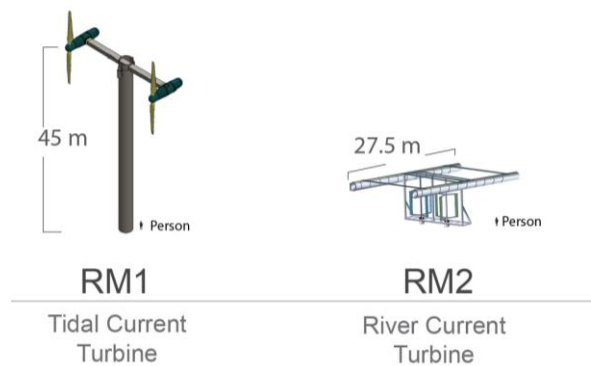RM3 — Wave Point Absorber

RM4 — Ocean Current Turbine

Figure 1. RMs 1, 2, 3, and 4 shown in approximate scale.

We calculated LCOE estimates (in $/kWh) for each RM over a range of installed capacities based on arrays of 1-, 10-, 50- and 100-units. Although not explicitly delineated as part of our methodology for designing MEC devices, we maintain that physical scaled model testing for device design and model validation is an essential part of the design and analysis process.

The design methodology and the RM devices and arrays developed through the RMP are intended to support DOE's MEC technology development and market acceleration efforts in the following ways:

- Provide a documented and transparent methodology for comparison to other methodologies developed by the MEC community for MEC device/array design and LCOE estimation.

- Provide reference marine energy resource sites (modeled on actual sites) to allow developers to assess their device's potential performance. These sites have considerable data on the hydrokinetic energy resource, site attributes (not inclusive of seabed conditions for all sites), and characterization of potential environmental risks. These sites also are generally prototypical of locations that are likely candidates for utility-scale (commercial-scale) MEC development, thus, providing a reference from which developers can assess technology competitiveness in the U.S. market.

- Identify key cost drivers and cost reduction pathways for prominent MEC archetypes.

- Provide LCOE estimates for prominent MEC archetypes.

- Provide numerical and experimental data sets that can be used to verify and validate MEC design tools and methods.

- Identify known gaps in the modeling and design tools needed to advance MEC technology. Each stage of advancement is assessed against DOE's Technology Readiness Levels (TRLs) from one to nine, with nine being a design that is commercially ready for production. As the

technology is studied, tested, and refined, it is expected that future entrepreneurs and researchers will develop the next generation of MEC devices.

- Provide guidance for environmental permitting of MECs, including following the National Environmental Policy Act (NEPA) process to achieve compliance. Environmental compliance efforts will include extensive siting characterization and conducting pre-installation studies required to meet acceptance by regulators and stakeholders. If the project meets environmental, operational, and other criteria and achieves all necessary regulatory permitting, then, post-installation studies and environmental monitoring will proceed, as required; certain types of monitoring will be required throughout the life of the project.

METHODOLOGY

Figure 2 illustrates the design methodology, including the iterations needed to meet key constraints imposed for structural design and for environmental compliance (refer to dashed lines from the decision boxes below the 'Design and Analysis' and 'Environmental Compliance' module boxes shown in the center of the flowchart). The methodology used for the four reference models (point designs) deviates in varying degrees from this idealized methodology. These deviations were due mainly to the limitations on resources available for this initial study. For example, weather windows, one of the inputs under 'Site Information' on the chart, were not calculated for the four reference model sites. Where applicable, we reference work done by others who have performed higher order analyses.
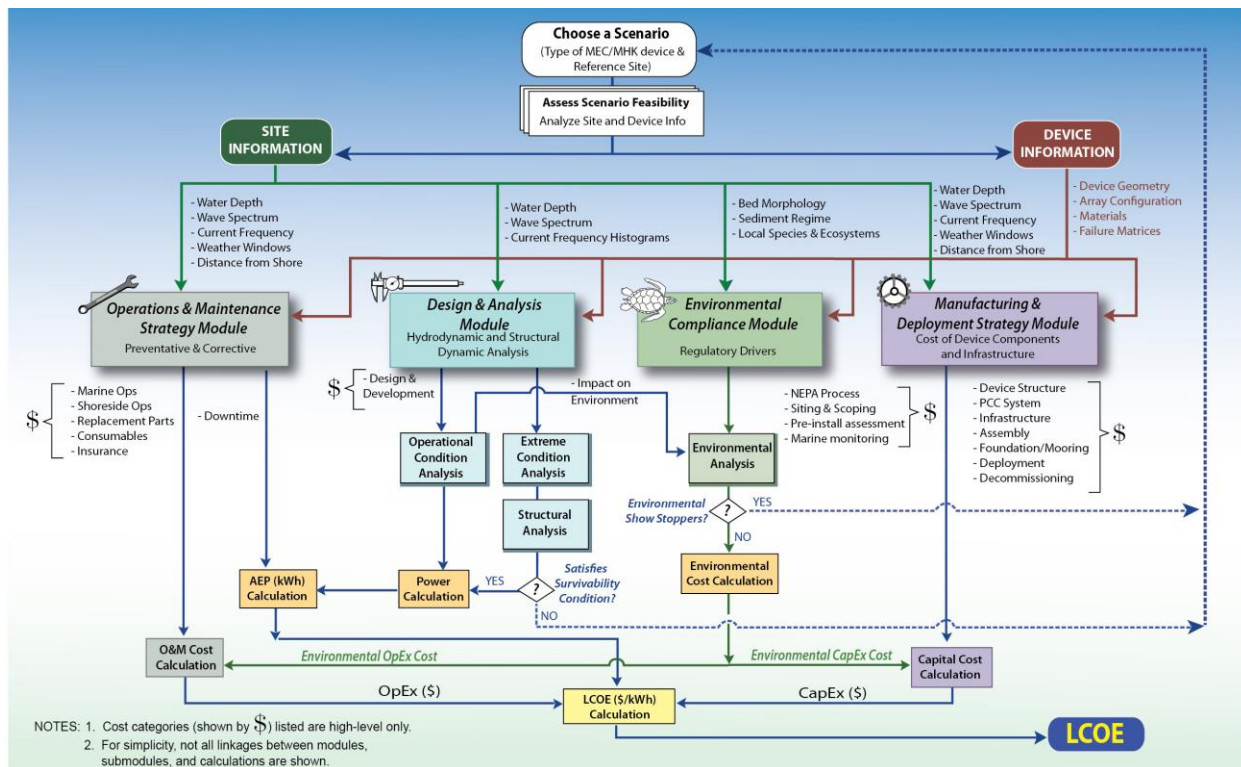

Figure 2. Methodology for design, analysis, and LCOE estimation for MEC technologies.

The methodology centers on four core modules:

1. The **Design & Analysis (D&A) Module** applies engineering models to design, analyze, and optimize power and structural performance for a given MEC device paired with its reference site resource. Output from this module determines the technical feasibility of the device/array and the potential AEP. The final design specifications provide the data needed to determine materials and manufacturing costs in the 'Manufacturing & Deployment (M&D) Strategy' Module.

2. The **Manufacturing & Deployment (M&D) Strategy Module** delineates the materials and manufacturing processes and deployment strategies that are adopted in order to determine

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CapEx associated with manufacturing the device and deploying it at different array scales. This includes CapEx for subcomponent materials based on structural analysis of extreme loadings, subsystem requirements to reduce O&M costs, and deployment (installation) costs. Deployment strategies include service vessel requirements and other considerations for the installation of the MEC devices and their associated infrastructure referred to as balance of system (BOS) components—examples would be the mooring components and the transmission cables connecting the device/array to the substation for grid connection.

3. The **Operations & Maintenance (O&M) Strategy Module** delineates an O&M strategy and identifies costs based on estimates of subcomponent and subsystem failure rates and service requirements for operations and other OpEx categories. O&M strategies include service vessel requirements to maintain the MEC devices and the array infrastructure. This module also accounts for expected operational availability—this is based on land-based wind plant/farm data—which determines the actual AEP considered in the LCOE estimate.

4. The **Environmental Compliance (EC) Module** details the site studies and environmental monitoring needs to meet regulatory siting and permitting requirements for deploying the Reference Model array at a particular reference site. EC costs are mainly CapEx because they occur before deployment and operation. Many monitoring activities, site studies, and related research work are critical for compliance with environmental regulations and permitting requirements (NEPA is the primary driver), addressing stakeholder input, and determining the overall feasibility of deploying the MEC device/array given all discovered factors. Both pre-installation environmental studies and—if deployment at the selected site is found acceptable—post-installation studies will be conducted as well as recurring environmental monitoring that will take place during the lifecycle of the device/array. Recurring, routine environmental monitoring costs after operations begin are treated as OpEx.

These four modules include various sub-modules (not all of which are shown on the flow chart) used for analysis, design iteration, and optimization to meet structural and environmental constraints.

RESULTS AND DISCUSSION

LCOE estimates (with ±30% uncertainty bars) for 10- and 100-unit arrays for all four RMs are shown in Figure 3. Projects with 10-units are considered most likely once the industry first reaches maturity. However, significant cost reductions can be gained with larger projects because of economies of scale.

For 10-unit arrays, the low LCOE for the ocean current turbine RM4 ($0.25/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. The LCOE for the tidal current turbine RM1 ($0.41/kWh) is slightly more than the values reported for offshore wind turbines. For the river current turbine RM2, the high LCOE ($0.80/kWh) is due to the low installed capacity factor and the spatial constraints inherent at a river site. The LCOE estimate for the WEC device RM3 ($1.45/kWh) is comparatively higher, but this largely reflects the lack of experience and tools available for designing this technology at the time of this study. 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 developed tools that could be leveraged to design the RM3 device. Critical innovations to improve performance of RM3, such as advanced controls that would regulate the device's motion to resonate with the wave frequency, were also not applied.
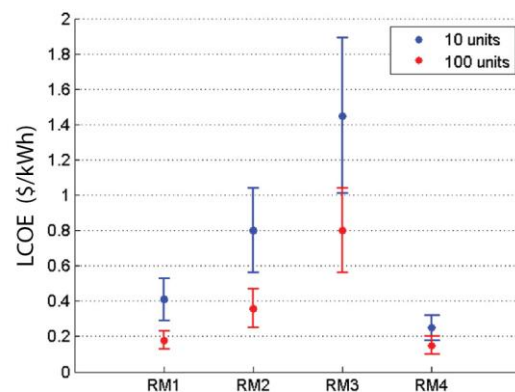

Figure 3. LCOE estimates for four reference MEC technology point designs.

One of the primary goals of this study was to identify key cost drivers to help focus future R&D efforts. For all CEC archetype 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, we acknowledge that environmental costs have medium

to high uncertainty and will be case dependent. Structural components and the power conversion chain (PCC) 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 device, RM3, 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. There are clear R&D needs in advanced controls to increase WEC performance as discussed in more detail below.

We fully recognize that the methodology we have developed requires improvements and we encourage its further development. The following discussion summarizes the weaknesses identified in design, analysis, performance, and cost modeling and provides recommendations for: (1) closing knowledge gaps to reduce uncertainty bands on performance and costs; and (2) improving technology performance with improved design optimization modeling and refining advanced control systems.

Power Performance and AEP Estimates

Scaled model testing of MEC devices and arrays is critical to narrow the uncertainties and increase confidence levels in the power performance predictions and AEP estimates. These power estimates are derived from several hydrodynamic models that are commonly used for analyzing MEC devices. Scaled model testing is also a prerequisite for a device to advance, in DOE's Technology Readiness Level (TRL) scale, to level 4 (TRL-4). At the TRL 4 stage, basic technological components of a sub-scale model have been integrated to validate design predictions and system level functionality; furthermore, the models and/or critical subsystems have been tested in a laboratory environment. Approximately half a dozen physical modeling experiments are completed, are underway, or are planned for scaled models of our RM devices or their rotors. These studies should provide more opportunities to validate the RM device designs and the models used for performance and AEP estimates. In order to facilitate further physical model testing and model validation, SolidWorks files (3D CAD software) of all RM device geometries are available for downloading from Sandia's Energy, Climate, and Infrastructure Security website at: http://energy.sandia.gov/rmp.

Operational Experience from Technology Analogues

Estimated CapEx and OpEx costs rely heavily on design, M&D, and O&M experience and actual data from land-based wind plants. To estimate RM device and array availability, and to calculate the AEP used in the LCOE estimate, we applied an operational availability level of 95% (the percentage of the time

the device is actively producing electricity). This percentage is equal to the 2011 operational availability benchmark reported for land-based wind plants surveyed in the United States by the Continuous Reliability Enhancement for Wind (CREW) database, a DOE-funded national reliability database. This is 2% less than the 2012 benchmark for wind plants, which had operational availability levels of 97% (Peters et al. 2012). Uncertainties in CapEx and OpEx costs can be narrowed further by incorporating empirical data from other, more mature, renewable energy technology analogues used to delineate M&D and O&M strategies and costs. Operational data from offshore wind plants would be particularly valuable because it would help quantify the additional costs associated with the challenges of marine operations. In the end, however, these costs can only be accurately assessed with actual operational experience of MEC technologies at commercial scales.

Operations Modeling

As demonstrated by Teillant et al. (2012), estimates for operational costs and device availability can be improved by applying more rigorous operational models (based on O&M experience with wind plants as well as from oil and gas exploration). For example, Teillant et al. (2012) apply weather windows to determine when conditions are suitable for operation of vessels and equipment required for preventative and corrective O&M tasks, such as installation, repair, inspection, and removal. Weather windows, which vary among the different resource types (e.g., wave environments compared to tidal current environments) and specific sites, were not considered in our O&M Strategy Module.

Design Optimization

Our RM device designs were developed primarily to calculate LCOE estimates. They are simple, robust, preliminary designs. Optimization of the performance of the RM devices was minimal and also varied among the four different RMs. For CEC RM devices, performance can be improved using well developed optimization methods used for wind turbines. For WEC RM devices, however, more fundamental R&D is needed in the area of real-time-weather forecasting and advanced control systems. Recent research shows that advanced controls can provide substantial enhancement to energy capture efficiency. Finally, until array optimization models are further developed, there remains large uncertainties in array costs covered under the M&D, O&M, and EC modules described above.

Environmental Compliance Costs

For this preliminary study, we assigned no OpEx costs for ongoing mitigation activities that would be required for managing identified environmental risks

that cannot be adequately reduced through improved engineering, operations, or siting. Until knowledge gaps can be better characterized and closed—including knowing the potential impacts of MEC devices and projects on the physical and biological environment (e.g., animal strike, noise levels, and electromagnetic fields [EMF]), it will not be possible to fully determine mitigation requirements and their costs.

CONCLUSIONS

We present a methodology for the economic analysis of four MEC Reference Models to include costs for designing, manufacturing, deploying, and operating commercial-scale MEC arrays. The methodology was applied to benchmark technical and economic performance, including LCOE for point designs of common MEC archetypes in $/kWh. Although, many costs are difficult to estimate at this time due to the lack of operational experience, particularly for the WEC device, RM3, the main contribution of this work is to disseminate a detailed cost analysis where all costs are clearly delineated. While the Reference Model technologies were only designed at the conceptual level (DOE Technology Readiness Level 3-4), they were assumed to be mature and commercially viable for the purpose of estimating annual energy production (AEP) and CapEx and OpEx costs.

We believe LCOE estimates (based on 10-unit arrays) for the current energy conversion (CEC) devices devices—RM1, RM2 and RM4—are in reasonable agreement with other published LCOE estimates and are defensible. The LCOE estimate for the RM3 WEC device, however, may be overly pessimistic. Unlike the turbine-based CEC RM designs, which benefited from decades of DOE laboratory R&D experience in wind turbine technologies, there was relatively little design experience and design and analysis tools at the time of this study that could be leveraged to design the RM3 WEC device.

We recognize that some of the costs used in the LCOE estimates may be perceived as optimistic by experienced MEC developers in a nascent industry, especially those costs benefiting from cost reductions as the number of units in an array increases; however, our goal was to reflect a mature MEC industry and the research community can always adjust these costs based on their judgment and experiences—and as operational experience is gained.

REFERENCES

Peters, V., Ogilvie A., and C. Bond. *Continuous Reliability Enhancement of Wind Database (CREW): Wind Plant Reliability Benchmark.* Technical Report: SAND2012-7328 (Available online http://energy.sandia.gov/crewbenchmark), Albuquerque, NM: Sandia National Laboratories, 2012.

Haas, K., Fritz, H., French, S., Smith, B., and V. Neary. *Assessment of Energy Production Potential from Tidal Streams in the United States.* Funded by U.S. DOE Wind & Water Power Program, Atlanta, GA: Georgia Tech Research Corporation, June 2011.

Hagerman, G., G. Scott, and P. Jacobson. *Mapping and Assessment of the United States Ocean Wave Energy.* EPRI Tech. Report: 1024637, Palo Alto, CA: Electric Power Research Institute (EPRI), Dec 2011.

Teillant, B., R. Costello, J. Weber, and and J. V. Ringwood. "Productivity and economic assessment of wave energy projects through operational simulations."." *Renewable Energy* 48 (2012): 220-230.