Levelized Cost of Energy Analysis of Marine and Hydrokinetic Reference Models

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LEVELIZED COST OF ENERGY ANALYSIS OF MARINE AND HYDROKINETIC REFERENCE MODELS

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ABSTRACT

In 2010, the U.S. Department of Energy initiated the development of six marine and hydrokinetic (MHK) energy converter reference models that are device point designs of well-known marine energy converters (MEC). Each device was designed to operate in a specific marine resource, instead of a generic device that can be deployed at any location. This method allows each device to be used as a reference model to benchmark future devices. The six designs consist of three current energy converters and three wave energy converters. The reference model project has generated both technical and economic data sets that are available in the public domain. The methodology to calculate the levelized cost of energy for the reference model project and an overall comparison of the cost of energy from these six reference-model designs are presented in this paper.

INTRODUCTION

Studies have shown that marine and hydrokinetic (MHK) renewable energy has the potential to provide a significant contribution to the electricity supply in the United States. The Electric Power Research Institute (EPRI) estimates that the total magnitude of the recoverable wave resource is approximately 1,170 Terra-Watt hours per year [1], while the combined ocean current, ocean tide, and U.S. river resource is approximately 500 Terra-Watt hours per year [2-4]. Combined the total MHK resource is nearly 1/3 of the U.S. electricity demand of approximately 4,000 Terra-Watt hours per year [5]. The available resource has renewed interest in research and development (R&D) efforts to develop marine energy conversion (MEC) technologies.

Although their resource potential is significant, MEC technologies are at early stages of development and will require further research to be economically competitive with other electricity generating technologies. To help mitigate this challenge, the U.S. Department of Energy (DOE) initiated the reference model (RM) project. The objectives of this project were to: 1) analyze nonproprietary devices that would be made available to the general public to allow for technical and economic benchmarking; and 2) assess the potential cost of energy and identify cost-reduction pathways and areas where additional research could be applied to best accelerate technology development to market readiness. Six MHK device point designs were developed in the RM project, including three current energy converters (CECs) and three wave energy converters (WECs). Each RM model was designed for specific marine resources, which were modeled after existing U.S. locations.

The RM study includes structural analysis, power output estimation, a power conversion chain system, and mooring designs. The results were used to estimate device capital cost and annual operation and maintenance (OpEx) costs. Device performance and costs were used for the economic analysis that included costs for designing, manufacturing, deploying, and operating single and commercial-scale MEC arrays for up to 100 devices [6–8].

Following a preliminary levelized cost of energy (LCOE) comparison for RM designs 1–4 [9], the objective of this study was to investigate the comparison of LCOE for all six RM models. In this paper, the RM model design concepts are reviewed. After describing the methodology for estimating the LCOE, the cost breakdown of the six

RM models for a single unit and for 10, 50, and 100 unit arrays is presented. Finally, a study on the overall LCOE comparison for 10-megawatt (MW) commercial-scale MEC arrays is presented.

RM MODEL DESIGN CONCEPT

The three CECs that were studied include a horizontal-axis tidal turbine, a vertical-axis riverine turbine, and a horizontal-axis open-ocean current turbine. The three WECs include a floating body point absorber, a pitching flap device, and an oscillating water column (OWC). The schematic of the CECs and WECs studied in the RM project are shown in Figure 1 and Figure 2, respectively.

FIGURE 1. SCHEMATIC OF CECS (RM1, RM2, RM4) (ADOPTED FROM [6])

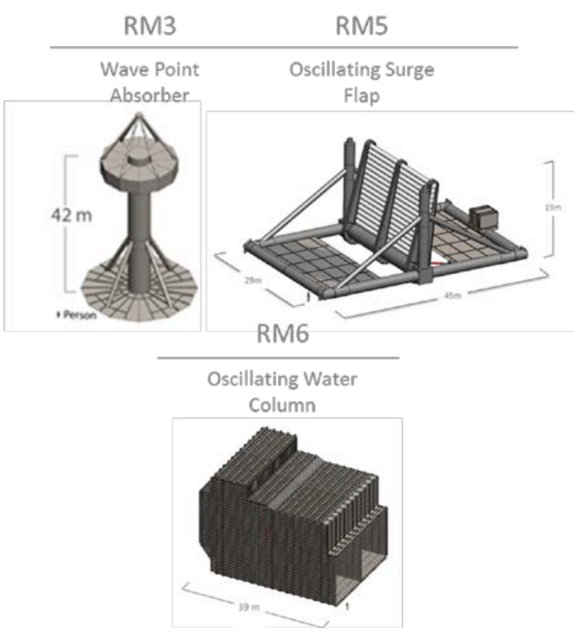

FIGURE 2. SCHEMATIC OF WECS (RM3, RM5, RM6) (ADOPTED FROM [6-8])

More details of the device design for the RM models are described in the RM project reports [7–9]. Brief descriptions of the six models studied in the RM are provided here.

- **RM1:** A dual-rotor, axial-flow tidal turbine (horizontal axis) designed for the reference location modeled after the Tacoma Narrows in Puget Sound, Washington.
- **RM2:** A dual-rotor, cross-flow river turbine designed for the reference location modeled after a section of the lower Mississippi river near Baton Rouge, Louisiana.
- **RM3:** A two-body floating-point absorber designed for the reference location modeled after a wave site near Eureka, in Humboldt County, California.
- **RM4:** A moored glider with four axial-flow turbines designed for an ocean current resource modeled after the Florida Strait within the Gulf Stream off the southeast coast of Florida near Boca Raton.
- **RM5:** A floating, oscillating surge WEC designed for the reference location modeled after a wave site near Eureka, in Humboldt County, California.
- **RM6:** A floating Backwards Bent Duct Buoy OWC designed for the reference location modeled after a wave site near Eureka, in Humboldt County, California.

The data created around these devices was intended to give future researchers and developers a set of reference data for MECs. It is important to note that although each device went through a rigorous design process, they did not incorporate any advanced materials, components, or control strategies. Instead, the six devices considered were used for techno-economic benchmarks of similar device configurations.

COST OF ENERGY METHODOLOGY

The lack of MEC devices being deployed in the United States can be attributed to the high cost of converting the resource into electricity. Although the marine resource is free, similar to wind and solar, the cost of converting that resource depends on many factors. One of the objectives associated with the RM project was to understand the largest cost drivers for each technology at different array scales.

Cost of Energy Estimate

LCOE is a term that DOE uses to determine the “break even” cost for a technology assuming a minimum rate of return. Analysis was performed in the RM project to determine the cost of electricity production for single unit, 10-unit, 50-unit, and 100-unit array sizes. Using these array sizes for each point design allows for a detailed breakdown of initial capital expenditures (CapEx) and annual operating expenditures (OpEx). This breakdown is necessary as it gives two of the four inputs required to calculate LCOE. The other two inputs include the annual energy production (AEP) provided to the grid, and the fixed charge rate (FCR). The AEP in the RM project was estimated based on the reference site resource [10–13] and the results from numerical simulations and experimental tests [14–17]. 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. The simplified LCOE can be represented using these inputs [18]:

$$\text{LCOE} = \frac{(\text{FCR} \times \text{CapEx}) + \text{OpEx}}{\text{AEP}} \tag{1}$$

CapEx and OpEx Costs

CapEx and OpEx costs are further broken down into a cost breakdown structure (CBS) that was developed in the RM project. The categories of the CBS used for all the reference models are shown in Table 1.

TABLE 1. COST CATEGORIES FOR CAPEX AND OPEX

CapEx	OpEx
Development	Insurance
Infrastructure	Post installation environmental
Mooring/foundation	Marine operations
Device structural components	Shore-side operations
Power take-off	Replacement parts
Subsystem integration & profit margin	Consumables
Installation	-
Contingency	-

CapEx costs are broken down even further depending on the specific design. This structure allowed the RM project team to focus on specific costs associated with each category, allowing for a more refined analysis for each device.

CURRENT ENERGY CONVERTER COST OF ENERGY

The CECs (RM1, RM2, and RM4) represent three different resource types for current energy. RM1 is a tidal current turbine, RM2 is a smaller river current turbine, and RM4 is an open ocean current turbine. The different resource conditions result in different capacity factor, which measures how much average electricity a MHK device generates for a period of time relative to the electricity it can produce at the rated power during the same period. Table 2 lists the capacity factor for the CEC models in the RM project and the rated power (installed capacity) for these devices.

TABLE 2. CEC CAPACITY FACTOR AND RATED POWER FOR A SINGLE UNIT

	Assumed Capacity Factor	Rated Power (kilowatts)
RM1	0.3	1115
RM2	0.3	90
RM4	0.7	4000

The smallest of the three is RM2 at only 90 kilowatts (kW); RM4 is designed for 4 MW, taking advantage of the high capacity factor because of the constancy of the Gulf Stream in the Florida Strait. Note that the wide rated power range and different resource conditions can create a bias when looking at LCOE for a particular array size. For example, a single RM4 device delivers approximately the same order of magnitude of AEP as the 100-unit RM2 array. Nevertheless, the trends associated with array size are still valuable in understanding cost drivers and potential cost reductions for different devices.

Moving from a single-unit deployment to a 10-unit deployment reduces LCOE between 65%-80%, depending on the device. The biggest contributor to this cost reduction is that OpEx and infrastructure costs are shared by multiple units. The percentages of these costs, as a function of LCOE, continue to drop as more units are deployed, although the largest reduction in LCOE happens between single- and 10-unit arrays, as shown in Table 3.

TABLE 3. CEC LCOE FOR SINGLE-UNIT, 10-UNIT, 50-UNIT, AND 100-UNIT ARRAY

	1-Unit	10-Unit	50-Unit	100-Unit
	($/kilowatt-hour)			
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

To demonstrate the change in the breakdown for a different array-size deployment, the LCOE breakdowns for a single-unit and 100-unit array are plotted in Figure 3 and Figure 4, respectively. The breakdowns show that the infrastructure and OpEx costs are the primary costs in the single-unit case, whereas the device structure and power take- off (PTO) are the primary cost drivers for the 100-unit array scenario. In particular, the OpEx cost for the single unit is dominated by the environmental monitoring cost because of the lack of operational environmental data for the MEC devices being deployed. This raises the uncertainty regarding the environmental impact from MHK devices and requires in-depth studies and monitoring. For the 100-unit array, all three CECs have a similar LCOE breakdown because the infrastructure cost diminishes for large array deployment. RM1 and RM4 are designed for ocean environments, which have similar breakdowns. On the other hand, RM2 is intended for river currents, which have a similar 100-unit breakdown but differ from the other CECs in the single-unit deployment because of higher development cost and lower infrastructure cost.

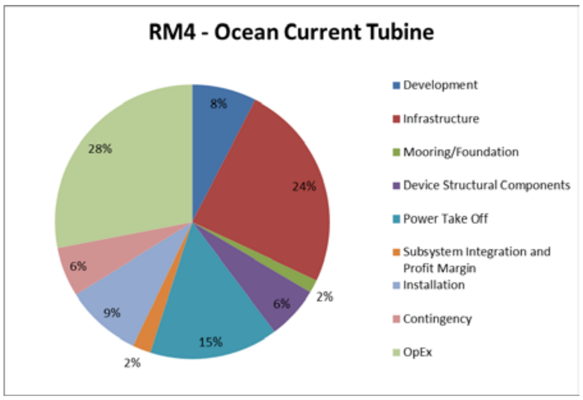

FIGURE 3. RM4 LCOE BREAKDOWN (SINGLE UNIT)

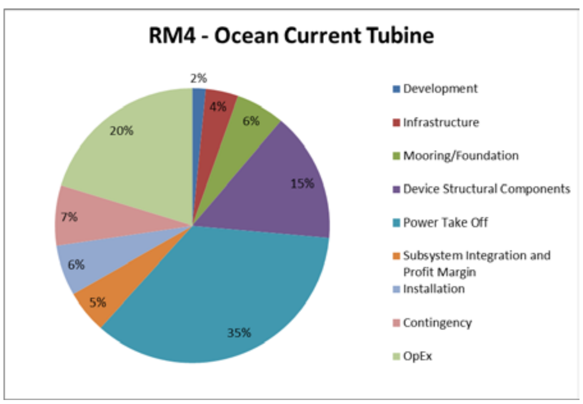

FIGURE 4. RM4 LCOE BREAKDOWN (100 UNIT)

As the arrays increase up to 100 units the cost distribution of LCOE shifts so that approximately three-quarters of LCOE is a result of the device structure, PTO, and annual OpEx costs. Although the cost of others components may be reduced, the greatest reduction in LCOE will be due to these three categories in addition to an increase in energy production (e.g., greater availability, increased capacity per structure, and so on).

WAVE ENERGY CONVERTER COST OF ENERGY

RM3 is a two-body floating-point absorber, RM5 is a floating oscillating surge device, and RM6 is an OWC. The WEC devices (RM3, RM5, and RM6) are all based on the same resource near Humboldt County, California. The resource conformity creates a smaller deviation of installed capacity when compared with the CEC models. Table 4 lists the capacity factor for the WEC models in the RM project and the rated power for these devices. Because the same capacity factor and wave resource were used when designing these three WECs and estimating their power output, the comparison of the rated power is not as significant between the WEC devices as it is for the CEC devices.

TABLE 4. WEC CAPACITY FACTOR AND RATED POWER FOR A SINGLE UNIT

	Assumed Capacity Factor	Rated Power (kW)
RM3	0.3	286
RM5	0.3	360
RM6	0.3	370

The WECs also have a large percentage of single-unit LCOE attributed to annual OpEx costs. In addition to the high OpEx costs, another significant cost driver for single-unit installations is the development costs, particularly the environmental cost for permitting and leasing. Unlike CECs, which have designs similar to wind turbines and can use the experience from the wind energy industry, WECs have a higher development cost that is attributed to the uncertainty caused by the variety of WEC sizes and working principles [19].

Similar to the CEC models, the WECs show a significant LCOE reduction as array size increases from single- to 10-unit deployments. The reduction in LCOE as a function of array size for RM3, RM5, and RM6 are shown in Table 5.

TABLE 5. LCOE FOR THE SINGLE-UNIT, 10-UNIT, 50-UNIT, AND 100-UNIT ARRAYS

	1-Unit	10-Unit	50-Unit	100-Unit
	($/kilowatt-hour)			
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

The reasoning for the relative difference in RM3 and RM5 LCOE when looking at single-unit and 10-unit arrays can be attributed to the estimated pre- and post-installation environmental costs. Some of this can be attributed to the varying foundation design, with the rest being caused by variations in assumptions between the three WEC devices [19, 20]. Although the assumptions have a significant impact at the single-unit scale, there is little impact on LCOE as the array goes to 100 units.

Figures 5 and 6 compare the LCOE breakdowns for RM5 at single-unit and 100-unit array deployments. The identical resource and similar installed capacity makes for a better side-by-side comparison of the WEC devices. Although there are subtle differences between RM3, RM5, and RM6, the percentage breakdown of LCOE is similar. The largest deviation is the contribution of structural costs; the WEC's LCOE is dominated by structural costs. The RM3 structural costs account for 37% of the LCOE at 100-unit deployments, whereas RM5 and RM6 are 41% and 52%, respectively. Much of this deviation can be associated with overdesign, particularly for RM6 [8]. Unlike CECs, the mooring cost has a bigger impact than that from PTO. High mooring costs are expected in these devices because all three WECs use floating platforms. Floating designs inherently require high mooring loads to resist power dissipation via device movement, particularly for RM5, where the device requires a taut mooring [6]. The relative costs of the PTO and device structure are shifted because of the large structural costs of the WEC devices. It is likely that a more structurally optimized design will reduce these costs.

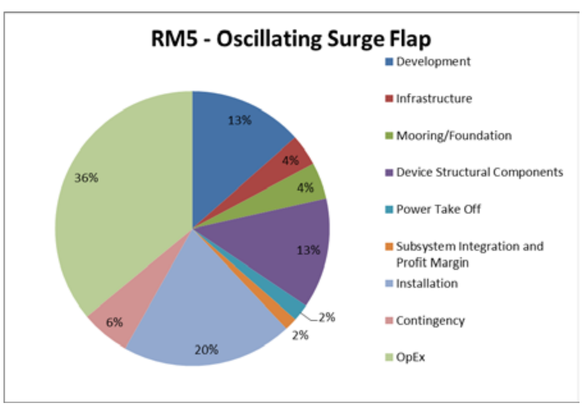

FIGURE 5. RM5 LCOE BREAKDOWN (SINGLE UNIT)

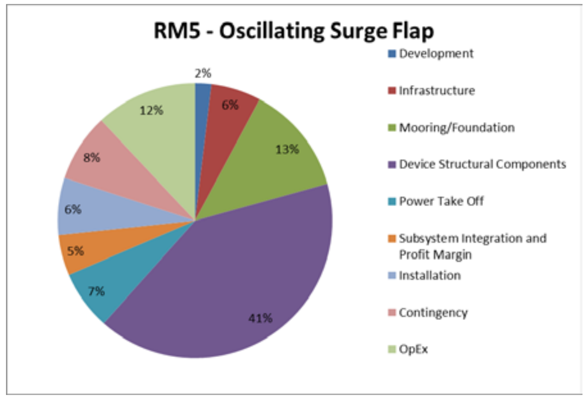

FIGURE 6. RM5 LCOE BREAKDOWN (100 UNIT)

10-MW SMALL COMMERCIAL-SCALE COMPARISON

The differences in the resource conditions and the device rated power make it unfair to compare the LCOE for the six MHK point designs studied in the RM project. To investigate the LCOE cost reduction due to increasing array size, a polynomial curve fit of the four array sizes was used. The LCOE is plotted against the installed capacity in Figure 7. The LCOE for each RM model was estimated at 10 MW for small commercial-scale, and the results are listed in Table 6. The LCOE for the 10-MW CECs are in the range between $0.3 per kilowatt-hour (kWh) and $0.5/kWh. In comparison, the LCOE values for the same 10-MW installed capacity WECs are in the range between$ 1.0/kWh and $1.5/kWh.

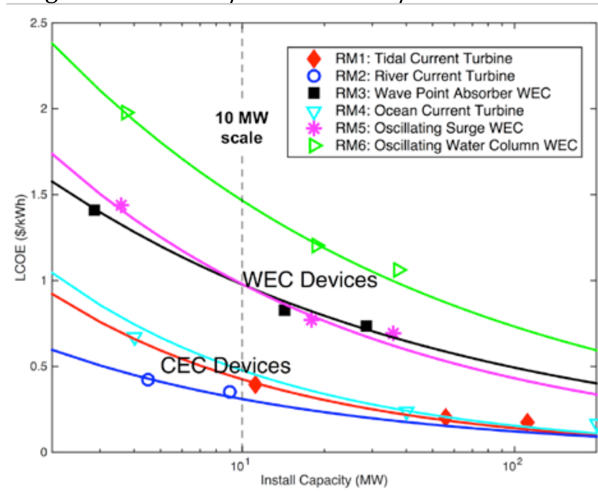

FIGURE 7. RM MODELS' LCOE FOR DIFFERENT INSTALLED CAPACITIES

TABLE 6. LCOE ESTIMATE FOR THE 10-MW SMALL COMMERCIAL-SCALE

RM Model	LCOE ($/kWh)
RM1	0.42
RM2	0.31
RM3	0.98
RM4	0.48
RM5	0.98
RM6	1.47

CONCLUSIONS

A study on the LCOE for six MEC reference model point designs is presented in this paper. The six designs consist of three CECs and three WECs. The LCOE was estimated based on four primary inputs, including CapEx, OpEx, AEP, and FCR. The cost breakdown of the six RM models was analyzed for up to a 100-unit array, and a study on the overall LCOE comparison of the models for 10-MW commercial-scale arrays were presented.

The study shows that CECs (e.g., 10 MW installed capacity) are within the range of early market adoption primarily because the CEC technologies are more mature then WECs. Much of the maturity associated with CEC is a result of the knowledge gained from offshore and land-based wind technology; however, technology advancements that will lead to significant LCOE reductions are still needed to be widely competitive. Cost reductions for CEC devices will most likely result from improving OpEx strategies and reducing PTO cost. WEC devices, on the other hand, are further behind on the market readiness scale, and there is little convergence on a standard WEC technology, particularly with respect to and device size. In addition, the WECs studied in this RM project are most likely overdesigned structurally, as mentioned in the last section. The systems can be further improved by implementing advanced control strategies to optimize their power performance. In addition to the cost reduction from OpEx and PTO, structure design innovation, and power performance improvement are two important areas that need additional research to accelerate WEC technology development to market readiness.

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