METHODOLOGY TO DETERMINE THE ACE WAVE ENERGY PRIZE METRIC

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INTRODUCTION

Wave energy harvesting technologies include a large number of archetypes that span the range of technology readiness levels (TRLs). Novel concepts and technical innovations continue to drive research and development (R&D) aimed at increasing energy capture efficiency and reducing costs as evidenced by a sustained growth in patent activity. However, funding is hard to secure for performance testing and evaluation of WEC devices in wave tanks at a meaningful scale. This is a problem for the industry since scaled WEC prototype tank testing, validation, and evaluation are key steps in the advancement of WEC technologies through the TRLs and the Technology Performance Levels (TPL) to reach commercialization and economic performance, respectively.

To address the R&D challenges and barriers experienced by many new and innovative technologies, the United States' Department of Energy's Wave Energy Prize was launched in 2014. The Prize contest encouraged the development of innovative deep-water wave energy technologies that at least double device performance above the state-of-the-art. The Prize attracted 92 teams with a goal of involving new entrants in the field, while motivating and inspiring existing developers and stakeholders.

Performance evaluation of energy conversion technologies typically weighs the cost of a project (implementing a technology as a single device or array of multiple devices) per unit energy capture (annual energy production) through a levelized cost of energy (LCOE) metric, e.g., [1]. However, an accurate LCOE estimate, e.g., [1] requires a significant amount of information on capital costs, e.g., infrastructure, mooring systems, installation costs, and Operation and Maintenance (O&M) costs, e.g., marine and shoreside O&M, environmental monitoring, and insurance. It is also difficult to estimate and compare LCOE for different technologies that have disparate TRLs; where significant uncertainties exist in materials, design and operation. As a result, a variety of reduced metrics serving as proxies to LCOE have been proposed to evaluate and compare different WEC technologies [2]. The ACE metric, detailed herein, is a reduced metric specifically designed for the Wave Energy Prize to provide an equitable comparison of low TRL Wave Energy Converter (WEC), concepts. The value of ACE for state-of-the-art deep-water WEC technologies (in 2014) was estimated at 1.5 m/$M for deployment in a representative West Coast wave climate of the United States. The Prize aims to at least double this, yielding a prize threshold of 3.0 m/$M as a requirement to win the prize. The methodology and application of the ACE metric used to evaluate the performance of the technologies that competed in the Wave Energy Prize is described herein.

ACE METRIC

The ACE metric is defined as the "Average Climate Capture Width per Characteristic Capital Expenditure" [3] which is determined from the ratio of two components, the average climate capture width (ACCW) to the characteristic capital expenditure (CCE):

$$ACE = \frac{ACCW}{CCE} \tag{1}$$

ACCW for a set of sea states at site *j* is defined as the weighted average of the absorbed power of a WEC device divided by the incident wave energy flux per meter crest width.

$$ACCW_j = \frac{\sum_{i=1}^{n} \Xi_{ij} \, \langle AP(i) \rangle}{\langle C_P(j) \rangle} \tag{2}$$

where n denotes the number of sea states used in the average, Ξ_{ij} is the scaling factor for sea state *i* at each location *j*, $\langle AP(i) \rangle$ is the average power absorbed by the WEC for sea state *i*, and $\langle C_P(j) \rangle$ is the incident average annual wave energy flux for site *j* [4]. ACCW was determined from the average power for each of the nine finalists as measured at the Naval Surface Warfare Center Carderock Division's Maneuvering and Seakeeping Basin, MASK.

The CCE is a first order estimate of the structural cost and is defined as the sum of the products of the material mass and the manufactured cost of the material per unit mass:

$$CCE = \sum_{k=1}^{L} m_k \cdot MMC_k \tag{3}$$

where L denotes the number of materials that comprise the WEC, m_k is the total mass of structural material k, and MMC is the manufactured cost per unit mass of material k.

DETERMINATION OF ACCW

Each WEC for the nine finalists was tested at 1:20th scale at the MASK basin and subjected to ten different irregular wave states (IWS). The ACCW was calculated from six unidirectional long crested waves that commonly occur off the west coast of the United States, including Alaska and Hawaii. These are summarized in Table 1, and the selection methodology can be found in [5,6]. The WECs were also subject to two bi-modal and multi-directional sea states and two storm sea states [6].

TABLE 1. PARAMETERS FOR THE SIX 1:20TH SCALE ACE SEA STATES.

Sea State Designation	T_P (s)	H_S (m)
IWS 1	1.63	0.117
IWS 2	2.20	0.132
IWS 3	2.58	0.268
IWS 4	2.84	0.103
IWS 5	3.41	0.292
IWS 6	3.69	0.163

ACCW was calculated as a composite average of the average power produced from the team WECs for seven different wave sites, Table 2 using:

$$\overline{ACCW} = \sum_{j=1}^{7} \frac{ACCW_j}{7} \tag{4}$$

where $\overline{ACCW}$ is the average ACCW for all six sea states at seven different locations. Note that the scaling factors do not add to 100% for each location to ensure the average annual wave energy flux for each is correct [5,6].

TABLE 2. SCALING FACTORS FOR EACH SEA STATE AT SEVEN DIFFERENT LOCATIONS.

Sea State	Scaling Factors for Each Climate (%)						
	Alaska	Washington	Northern Oregon	Oregon	Northern California	Southern California	Hawaii
IWS 1	24.3	13.7	15.5	17.5	20.7	15.2	32.8
IWS 2	33.2	27.7	30.7	26.8	23.0	27.0	24.5
IWS 3	7.5	4.1	5.6	5.8	1.2	1.4	0.1
IWS 4	20.0	33.8	34.4	29.5	46.6	39.1	13.3
IWS 5	2.4	2.2	3.7	3.4	1.6	1.0	0.0
IWS 6	1.2	4.5	4.2	5.4	6.4	9.5	1.3
	Average Annual Wave Energy Flux (kW/m)						
$\langle C_P(j) \rangle$	35.5	32.7	39.3	37.9	31.5	31.2	16.8

DETERMINATION OF CCE

Estimating the Capital Expenditure (CapEx) of an early stage, low TRL, WEC is difficult and uncertain. Analysis of the WEC architypes studied in the DOE reference model project concluded that the structural cost is the largest contributor to LCOE, between 37-52% [7]. Therefore, as a proxy to the CapEx, the CCE is defined as the cost of the load bearing structure. Under this approach, the costs of the PTO, mooring system, anchors, umbilical, power electronics and non-load bearing structure are not included. While the ACE metric did not include significant capital costs, e.g., the PTO, or O&M costs, these costs were accounted for indirectly through additional criteria factors within a hydrodynamic performance quality (HPQ) metric [3].

The structural mass of the CCE includes the following:

- Any structure that interacts with the wave environment, including any external ballast housing, and potentially the ballast if determined to be a significant cost contributor.

- Any supporting structures used to resist forces in the power conversion chain
- Components central to the load path/force flow path. This includes power producing and non-power producing loads (i.e. drag loads) and Any components of the power conversion chain that are integrated into the structure
- Foundations and components rigidly attached to the WEC which can include structures required to raise or lower a device into the water column (e.g. Jackup Barge) and structures required for pre-loading and/or device placement, providing reactional reference to sea bed (e.g. Gravity Base)

Any WEC designs that are comprised of components that do not clearly fit the guidelines were evaluated by the nine Prize judges. The first stage of the competition had nine judges to review and down select entries through a TPL assessment to the 20 teams proceeding to the second stage of the competition. In the remaining stages, five judges reviewed all test results and documents.

The CCE is calculated for each structural component and grouped by like materials. The CCE is determined by expanding equation 3:

$$CCE = \sum_{k=1}^{L} \rho_k \cdot RST_k \cdot MMC_k \qquad (5)$$

where RST_k is the representative structural thickness of material k and ρ_k is the density of material of material k. The RST for each material is calculated using the following equation;

$$RST_k = \frac{\sum_{n=1}^{\varepsilon} m_n^k}{\rho_k \cdot \sum_{n=1}^{\varepsilon} A_n^k} \qquad (6)$$

where, ε is the number of components that are manufactured from material k, m_n^k is the mass of each component n which is made of material k, A_n^k is the simplified surface area of component n of material k.

The simplified surface area A_n^k is used to approximate the geometry of component n. To ensure equitable modeling of all components, all stiffeners and support members that do not directly contribute to the power conversion path are excluded from the surface area. Figure 1 and Figure 2 show how the surface area is simplified for Reference Model #3 (RM3) [1].

As per the prize rules [3], the RST is a scalar quantity that is used to determine the total structural mass when multiplied by the surface area of the device. The RST is a single uniform thickness used to approximate the average material thickness of each simplified component (including stiffeners etc). The RST can be visualized by melting down the structural of a component and "casting" it in the simplified shape. This means that all stiffeners and support structures are "lumped" together. A simple representation of the RST is shown in Figure 3 with a flat plate. The original structure includes a grid of stiffeners with a thin hull. That same quantity of material is then represented by a solid plate with the thickness given by the RST.

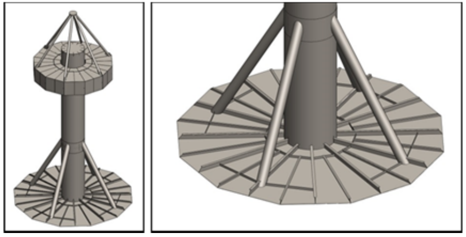

FIGURE 1: ORIGINAL RM3 GEOMETRY

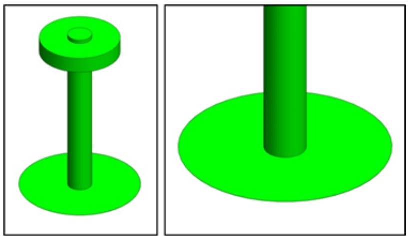

FIGURE 2: SIMPLIFIED RM3 GEOMETRY

FIGURE 3: VISUAL REPRESENTATION OF THE RST FOR A COMPONTENT ORIGINALLY COMPRIZED OF BEAMS

For the RM project, it was found that the largest load cases typically result during device operation. Additionally, many WECs operate under the assumption that they will not produce power during storm conditions reducing extreme loads. Thus, the RST for the each team was calculated using loads estimated for the same simplified set of expected WEC operating conditions derived from Humboldt Bay, California. All hydrodynamic design loads were specified for a 2.25m wave with a period of 16.5s. Although this does not represent the most likely operation point for WECs, it is representative of loads from the top 70th percentile waves at the Humboldt Bay location.

Structural models were chosen for each component of each WEC based on complexity. The lowest-order models that provided an accurate result where chosen. For straightforward structures, equivalent beam and flat plate models were used. The beam and flat plate models take simple geometries (e.g. box structures, cylinders, plate structures, etc.) and apply a series of transverse and longitudinal stiffeners (e.g. Flat Stiffeners, I-Beams, T-Stiffeners, etc.) to an external hull or skin. The number of stiffeners, and type of stiffener, are run through an algorithm which optimizes the structure for the minimum weight while maintaining an allowable stress. For more complex structures, or in instances where the simplified models would yield high levels of uncertainty, finite element models were employed. The output of each model is the total mass of each component, or set of components. The RST estimates were made without prior knowledge of device dynamics in operation. For this reason, the RST was provided with lower and higher bounds to account for when the device operation deviated from expected operation. The lower and higher bounds were calculated using load factors that were 14.3% lower and 14.3% higher than the nominal case, respectively. The judges then chose the RST value that was most appropriate based on observation of the device operation during testing in the ten waves.

After the RST and area were defined for each material, and the appropriate mass has been calculated, the total cost for each material is calculated using the MMC. The MMC is a scalar value that represents the total cost to manufacture the components at full production scale on a per unit mass basis. Therefore, the MMC includes costs of the raw material, fabrication, forming, and assembly. In practice, the value of MMC can vary due to material suppliers, complexity of manufacturing the device, number of subsystems to be assembled into the devices, along with many other intangible factors. For these reasons, three values were used (low, med, high) and the judging panel selected the MMC value based on the application of these factors.

The MMC values were selected using the combination of both public and internal offshore wind cost models, RM cost inputs, material case studies, and cost estimates for like structures (i.e. structures that utilize material of interest that are able to be built at similar scale). The values used are not intended to replace more detailed cost models and/or fabrication quotes, but they allow for quick comparison and consistency across different device types.

CONCLUSIONS

The ACE metric is an early stage proxy, or *reduced performance metric*, for the LCOE that allows equitable and consistent performance evaluation across the broad range of early stage archetypes competing in the Wave Energy Prize. This metric successfully integrated energy capture measurements from testing with cost estimates of the structure. Values for the $\overline{ACCW}$, normalized by the largest value, ranged from 0.03 to 1 m/m and they were typically proportional to the size of the absorber element(s). Values for the CCE, normalized by the largest value, ranged from 0.003 to 1 \$/\$ with an average value of 0.16 \$/\$. CCE values were driven by device size and wave loading. The ACE values ranged from less than 0.1 to 7.6 m/\$M, with four teams exceeding the threshold value of 3.0 m/\$M.

While the ACE metric was not a comprehensive measure of the total capital costs, or the O&M costs, undesirable attributes that affect these costs were accounted for indirectly through the hydrodynamic performance quality (HPQ) metric [3]; applied by judges in the final technology gate to rank finalists.

It is noted that testing was part of the competition and test duration was limited to one week for each team, without exception. Not all teams were able to test in all waves and some teams did not have their WECs fully functional for all tests.

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