Renewable and Sustainable Energy Reviews 98 (2018) 79–91

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Evaluation of performance metrics for the Wave Energy Prize converters tested at 1/20th scale

Ann Dallman[a,*], Dale S. Jenne[b], Vincent Neary[a], Frederick Driscoll[b], Robert Thresher[b], Budi Gunawan[a]

[a] Sandia National Laboratories (SNL), Albuquerque, NM, USA
[b] National Renewable Energy Laboratory (NREL), Golden, CO, USA

ARTICLE INFO

Keywords:
Wave energy converters
Wave Energy Prize
Performance database
Performance metrics
Tank testing
MASK basin

ABSTRACT

It is expected that wave energy technologies will play a future role in providing clean renewable energy and diversifying energy portfolios; however, they are still at an early stage of development compared to other renewables, with varying archetypes proposed. As technologies advance toward commercialization, benchmarking is needed to quantify performance and costs. In this review, experimental datasets of Wave Energy Converter (WEC) devices tested in the final stage of the Wave Energy Prize (WEPrize) are compared and ranked using performance metrics found in the literature and those developed as WEPrize judging metrics at both U.S. and European representative wave climates. Because the WEPrize devices were tested under a set of identical sea states, which ranged from typical operating conditions to extreme storm events, consistent datasets were produced to facilitate comparison. This allows for a rare addition to the open literature on device performance trends. In addition, a reevaluation of trends established in previous power performance benchmarking studies is given. Trends found in previous studies were confirmed, except for the absorbed energy per characteristic mass metric, in which some of the WEPrize devices had higher values. Each of the metrics considered in this study has limitations due to the assumptions in simplifying the economic potential (e.g., power absorbed vs. a proxy to cost). In addition, each of these proxies is limited to the capital cost of a device, unlike the final metric used in the WEPrize, HPQ, which includes limited proxies of operational and capital expenditures, as well as array considerations. Recommendations are given for the use and potential modification of the metrics considered. Specifically, it is recommended that the ACE metric (from the WEPrize) be modified to more accurately include the other important system costs, such as the PTO and mooring, as well as installation, operation and maintenance costs.

1. Introduction

The global need to diversify energy portfolios, expand energy supplies and reduce carbon emissions, has motivated research and development (R&D) of wave energy conversion (WEC) technologies that convert the potential and kinetic energy contained in ocean waves and swells into electricity [1]. Dozens of WEC devices comprising about half a dozen different WEC archetypes (point absorbers, attenuators, oscillating surge, overtopping, oscillating water columns) have been researched, tested and demonstrated over several decades [2–4]. However, most of these R&D efforts have focused on advancing a single device. With little incentive to publish results, data has often been too limited and inconsistent to permit normalized performance comparisons among different devices and archetypes [5]. Ranking devices and archetypes to discern performance trends has been difficult because the performance of each device evaluated is sensitive to the quality of the test conducted and the resource used, quality of the data, and differences in the maturity of the devices.

Despite these challenges there is a need to conduct performance benchmarking studies on a regular basis to elucidate performance trends and progress among different WEC devices and archetypes, as well as potential technology advancement and cost-reduction pathways. Previous benchmarking studies have addressed published data limitations by normalizing performance data, using numerical models and assumptions to derive inputs for the performance metrics considered, e.g., [5,6]. Others have developed non-proprietary reference point designs of WEC archetypes, e.g., [7] to quantify performance and cost benchmarks, and identify cost reduction pathways. The

* Corresponding author.
E-mail address: ardallm@sandia.gov (A. Dallman).

https://doi.org/10.1016/j.rser.2018.09.002
Received 31 January 2018; Received in revised form 16 July 2018; Accepted 3 September 2018
1364-0321/

Nomenclature

AAE	annual absorbed energy
ACE	average climate capture width divided by characteristic capital expenditure
ACCW	average climate capture width
AEP	annual energy production
CCE	characteristic capital expenditure
CP	incident wave energy flux
CWR	capture width ratio
DOE	United States Department of Energy
HPQ	hydrodynamic performance quality
IWS	irregular wave state
LCOE	levelized cost of energy
MASK	Maneuvering and Seakeeping basin
NSWC	Naval Surface Warfare Center
OWC	oscillating water column
OWSC	oscillating wave surge converters
PTO	power-take-off
RM	DOE Reference Model
RMS	root-mean-square
WEC	wave energy converter
WEPrize	U.S. DOE Wave Energy Prize

performance metrics in these benchmarking studies vary, with some studies comparing normalized hydrodynamic performance of different devices and archetypes, e.g., Babarit [6], others comparing levelized costs of energy (LCOE), e.g., [7–9], and others comparing normalized reduced cost-performance metrics, e.g., the annual absorbed energy per characteristic mass [5].

As hydrodynamic and power performance metrics are relatively simple to extrapolate from published data, e.g., capture-width-ratio (CWR), benchmarking studies using these metrics can include a large enough number of devices and archetypes to discern potential trends, e.g., [6]. In fact, among the studies reviewed here, [6] is the only one that found any discernible performance differences between the devices evaluated. Values of CWR for fixed oscillating wave surge converters (OWSC) were notably higher than heave activated and oscillating water column (OWC) archetypes. While CWR and other hydrodynamic/power performance metrics are important performance attributes to consider when selecting a generating technology, they do not provide a complete basis for assessing the technology's investment potential because it does not include cost.

Levelized cost of energy (LCOE), the per-kilowatt-hour cost of building and operating a generating technology over an assumed life-cycle, is the standard and ultimate measure of cost-performance (competitiveness) for an energy generating technology [9]. But LCOE is difficult to estimate accurately for nascent technologies with little operational experience and large uncertainties in costs. For this reason, researchers, e.g., [5], have introduced reduced cost-performance metrics that can account for the main cost drivers. These metrics provide some measure of the investment potential of the technology, and attempt to facilitate a practical approach to update and extend performance databases until operational experience can narrow uncertainty gaps.

Babarit et al. [5] found that normalizing annual absorbed energy by a characteristic mass, surface area, and root-mean-square (RMS) power-take-off (PTO) force, resulted in similar cost-performance for eight different devices representing three different archetypes. Performance ranking was dependent on the cost-performance metric, reflecting, albeit at a low fidelity, key cost drivers for the technology and potential cost reduction pathways. For example, a relatively low value for the cost-performance metric using mass would indicate efforts should focus on reducing structural costs. A relatively low value for the cost-performance metric using PTO force would indicate efforts should focus on reducing peak to average PTO loads. Some devices were more sensitive to the metric used than others. The study of Babarit et al. [5] suggests the need to develop higher-fidelity cost-performance metrics that include some of the more important costs included in an LCOE calculation, but avoids other costs with high uncertainty.

In the present study, experimental datasets from 1/20th physical model scale tests, generated as part of the US Department of Energy's (DOE) Wave Energy Prize (WEPrize) [10,11], were used to calculate a variety of performance metrics, including a reduced LCOE metric developed for the WEPrize, and normalized hydrodynamic and cost performance metrics used in the benchmarking studies of Babarit et al. [5,6]. As these datasets were collected using consistent methodologies from high-quality physical model tests, they present a rare opportunity to: 1) Compare, rank and benchmark the performance of different WEC devices; 2) Evaluate the effect of different performance metrics on ranking; and 3) Reevaluate performance trends observed by Babarit et al. [5,6].

While this paper focuses on a performance comparison between the WEPrize WECs and between other WEC technologies and concepts, it must be noted that the WEPrize was a competition carried out over a period of just over 1.5 years. The contest had very aggressive timelines and many contestants developed their WEC from a concept through to a 1/20th scale physical model. These scaled models do not completely represent a full-scale implementation (e.g., full PTO implementation and efficiencies considered). At 1/20th scale it would be physically impossible to have the test article PTOs fully replicate the working principles and efficiencies of full-scale PTOs, so only the wave to test article energy conversion was measured. Furthermore, given the focus on early stage innovative concepts and the short timeline for the WEPrize, it seemed unrealistic to ask the contestants to develop a complete cost estimate for their designs, hence a performance metric was used in place of levelized cost of energy to judge these early stage, low TRL concepts.

For each WEPrize device evaluated herein, the data were collected from a one-week intensive test campaign where the teams had much less time than what would be available in a typical model test to setup their device, fine tune their sensors and DAS, optimize their controller, and fix any issues. Thus, because of the short development duration and short test duration, the performance measures do not necessarily reflect the full potential or best results from any device (see Appendix A).

2. Testing facility

The WEPrize data considered in the present study is from the final round of testing [11] which occurred at the Maneuvering and Seakeeping (MASK) Basin at the Carderock Division of the Naval Surface Warfare Center (NSWC) in West Bethesda, Maryland. Testing at the MASK basin used a Froude-scale factor of 20 (e.g. each team tested 1/20th scale physical models). The MASK is 98.3 m by 61.7 m in area and is 6.1 m deep at the WEPrize testing location. The wavemaker can produce multi-directional and short crested seas, multiple sea states at various headings, and synthesize wave grouping and episodic events. It has 216 pivoting paddles along two adjacent sides of the basin, and each paddle is 0.658 m wide, with a hinge depth of 2.5 m. It can produce a fully developed seaway (Pierson-Moskowitz spectral distribution) of 35 cm in significant wave height and high steepness focused waves of 50 cm in significant height [12]. The sea states used for the WEPrize included both head and off-head directions, and the directional configuration is shown in Fig. 1.

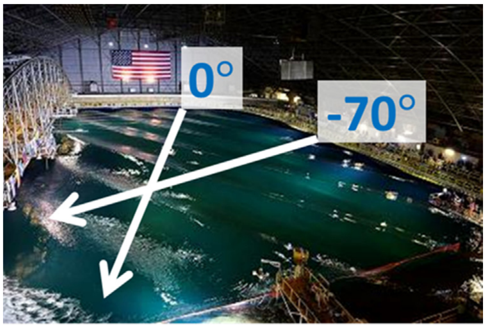

Fig. 1. MASK basin, with incoming wave directions specified for the WEPrize test conditions.

3. Wave energy converter performance metrics

This study calculated several performance metrics, including the capture width ratio, CWR (the hydrodynamic performance metric reviewed by Babarit [6]), the annual mean absorbed power [kW] and reduced cost-performance metrics introduced by Babarit et al. [5], and a reduced cost-performance metric developed for the WEPrize [13]. The reduced cost performance metrics used in this study include:

- Capture width/characteristic device diameter (CWR)
- Annual absorbed energy/characteristic mass [kWh/kg]
- Annual absorbed energy/wetted surface area [MWh/m^2]
- Annual absorbed energy/RMS PTO force [kWh/N]
- Capture width/characteristic capital expenditure (ACE) [m/$M]

The ACE metric was developed for the WEPrize to evaluate different WEC devices at early stages of technology development when information is insufficient to calculate a full LCOE. ACE is defined as:

$$ACE = \frac{ACCW}{CCE} \quad (1)$$

where Average Climate Capture Width (ACCW) is a measure of the effectiveness of a WEC at absorbing power from the incident wave energy field in units of meters [m], and Characteristic Capital Expenditure (CCE) is a measure of the capital expenditure in commercial production of the load bearing device structure in units of millions of dollars [$M]. The ACE metric, in the simplest terms, is the ratio of device performance (capture width in m) to device structural cost (in $M). A complete description of the development and explanation for the ACE metric can be found in Jenne et al. [13].

In addition to the ACE metric, the WEPrize utilized the hydrodynamic performance quality (HPQ) metrics to determine the final ACE ranking of the WEPrize teams that passed a designated ACE threshold. HPQ metrics can be visualized as the ACE score multiplied by factors that would increase or decrease the ACE value depending on the device's performance during testing. The multipliers used were based on the following measured HPQ metrics, where the multiplication factors were determined with inputs from the judges:

- mooring loads,
- station keeping (watch circle),
- peak to average absorbed power,
- PTO behavior (end stop impacts),
- absorbed power in realistic (bimodal) seas, and
- control effort expended.

Typically, the HPQ multiplication factors had an impact of plus or minus ten percent on the final ACE ranking.

The CWR metric is presented for dozens of WEC devices in [6], and these are compared in this paper to the top seven finalists of the WEPrize. This addition to the wide variety of archetypes in [6] allows for a broad comparison of technologies. Because the majority of the high energy U.S. wave resource is on the West Coast and the water depth increases rapidly, the WEPrize required devices that would operate in deep water [10], whereas the CWR database [6] included shallow and deep water devices, and a variety of fixed bottom and floating devices. Babarit et al. [5] evaluated eight devices in their numerical benchmarking study, but three of these devices are shallow water devices. Therefore, only the five deep water devices are compared to WEPrize devices for the four metrics in [5] for the sake of consistency. The devices included in this evaluation are described in the next section.

It is noted that the WEPrize did not directly use the same metrics as [5]. Thus to ensure consistent results, several additional steps were taken: additional parameters were calculated beyond what was done for the WEPrize, and additional processing of the data was performed in a manner as similar as possible to [5]. When insufficient information was available from WEPrize testing, the values of the metrics in [5] were modified. For example, the total mass and surface area of the WEPrize teams was readily available, but the wetted surface area had to be measured or estimated to compare to Babarit et al. [5]. Furthermore, the mass of the WEPrize teams only included the load bearing structure, and did not include moorings or foundations. Deeper water devices in [5] that had an additional factor added to the characteristic mass or wetted surface area to account for moorings or anchors/foundations were adjusted to allow a fair comparison with WEPrize technologies using data given in the full report of the WEC numerical benchmarking project [14].

For the absorbed energy per RMS of PTO force, there are limitations to the number of data points considered in this study. For WEPrize devices with rotary PTOs that transform absorbed power as the product of torque and angular velocity, the linear PTO force values were not available, and would require a number of assumptions to convert to a representative linear PTO force. Therefore, only four of the WEPrize devices are compared with this metric. In addition, only three of the five deep water devices have absorbed energy per RMS of PTO force reported in [5].

For the wave resource and absorbed energy, Babarit et al. [5] used

Table 1
ACE sea states and scaling factors.

Sea State	T_P	H_S	Dir	Scaling Factors for Each Climate						
	(s)	(m)	(deg)	AK	WA	N. OR	OR	N. CA	S. CA	HI
IWS 1	7.31	2.34	10.0	0.243	0.137	0.155	0.175	0.207	0.152	0.328
IWS 2	9.86	2.64	0.0	0.332	0.277	0.307	0.268	0.230	0.270	0.245
IWS 3	11.52	5.36	− 70	0.075	0.041	0.056	0.058	0.012	0.014	0.001
IWS 4	12.71	2.06	− 10.0	0.200	0.338	0.344	0.295	0.466	0.391	0.133
IWS 5	15.23	5.84	0.00	0.024	0.022	0.037	0.034	0.16	0.010	0.0
IWS 6	16.50	3.26	0.00	0.012	0.045	0.042	0.054	0.064	0.095	0.013
				Average Annual Wave Energy Flux (CP_j, kW/m)						
				35.5	32.7	39.3	37.9	31.5	31.2	16.8

full scatter diagrams (or joint probability distributions, JPDs) of sea states and power matrices for their numerical study. However, as the WEPrize used tank testing data, absorbed power was directly measured to evaluate device performance. Also, due to the tight testing schedule required to conduct the WEPrize, only 10 sea states were simulated in the tank. Details of the sea states simulated are described in Bull and Dallman [15]. Sea states used for the ACE calculation are listed below in Table 1. Due to the limited number of runs, the overall capture width had to be calculated with specific weightings to represent a full wave climate. The full wave climate for the WEPrize consisted of seven distinct climates from locations along the U.S. West Coast, as well as Alaska and Hawaii. Therefore, the absorbed power for each of the six sea states was multiplied by the individual scaling factors for a location, and the sum was divided by the associated location's incident wave energy flux per meter crest width to come up with the individual capture width, $ACCW_j$. The final ACCW is calculated as an average over the seven individual locations. More details are provided in Jenne et al. [13] and the WEPrize rules [10]. For this study, the annual absorbed energy (AAE, [kWh]) for the WEPrize devices was estimated as the average of the individual $ACCW_j$ values [m] for each climate, multiplied by the incident wave energy flux, CP_j [kW/m] for each climate and the average number of hours in a year (8766 [h], which averages three years of 8760 h and one leap year of 8784 h):

$$AAE = \frac{\sum_{j=1}^{7} 8766\, ACCW_j\, CP_j}{7} \tag{2}$$

Babarit et al. [5] evaluated performance at five European wave climates that are different than those used in the WEPrize. Each climate in the WEPrize had individual scaling factors for each sea state to properly represent the climate, including average annual power, as described in [5,6]. For this study, the five additional European climates were analyzed in the same way as the prize climates, and scaling factors were determined for each so that the metrics could be calculated at the five representative European climates as well (Table 2).

4. WEC devices

The five deep water devices from Babarit et al. [5] are compared to the WEPrize devices in this study. Among those evaluated in [5], the first is a small bottom-referenced heaving buoy (Bref-HB), which is an axisymmetric buoy with ellipsoidal cross section floating on the ocean surface. The PTO consists of a linear generator inside a steel hull mounted on a concrete ballast structure on the sea bottom. It is expected to operate in 40–100 m depth (considered intermediate to deep), whereas the rest of the devices are expected to operate in deep water. The second device is a floating two-body heaving converter (F-2HB), which is an axisymmetric self-reacting two-body heave system. A torus slides along a cylindrical float, and the device has a hydraulic PTO system. The third device is a floating heave-buoy array (F-HBA), which is composed of many heaving buoys connected to a common submerged reference structure. The submerged structure includes a hydraulic PTO system. The fourth device is a floating three-body oscillating flap device (F-3OF), which consists of four surface piercing hinged flaps which are all connected to a floating frame. The relative motion between each flap and the structure is converted to energy with a hydraulic PTO. The fifth device is a floating oscillating water column (F-OWC), known as a backward bent duct buoy (BBDB). It has a single air chamber, and the PTO consists of an air turbine connected to an electrical generator.

For the WEPrize devices, only seven finalists are included in this comparison. Two of the devices are not included because the data were questionable and the judges were not confident in the applied scaling. As previously mentioned, data used to evaluate the WEPrize devices are from a competition and not from a conventional model test. Thus, results do not necessarily reflect the full potential or best results from a particular device (see Appendix A). Test plans, data, and images from the WEPrize are available on the DOE's MHKDR site (https://mhkdr.openei.org, [16–22]). The seven WEPrize devices considered in this study can be found on the WEPrize website (https://waveenergyprize.org/teams/), and are also summarized here.

- The AquaHarmonics's device is a point absorber with latching/declutching control (the only device that had a control system that worked as designed).
- The CalWave Power Technologies device is a submerged pressure differential device (areal absorber).
- Waveswing America's device is a sub-sea pressure-differential point-absorber.
- Oscilla Power's device is a two-body, multi-mode point absorber.
- RTI Wave Power's device is a wave terminator using a floodable/submergible elongated wave front parallel float.
- Sea Potential's device is a two-body, multi-mode point absorber.
- Harvest Wave Energy's device is a combined OWSC (oscillating wave surge converter) and heaving device.

It should be noted that during the WEPrize 1/20th scale testing, one of Sea Potential's mooring load cells failed and was replaced with one loaned from the test facility. While this made the data from one out of three of their PTO's ineligible for consideration in the WEPrize analysis and judging, those data are however considered in this study. Both results are presented in this analysis and for clarity, 'Sea Potential' in plots below signifies the official WEPrize results, and 'Sea Potential*' (with an asterisk) signifies data with all three PTOs.

The WEPrize devices can be classified in terms of Babarit [6] definitions as:

- AquaHarmonics: heaving device, like the Bref-HB device.
- CalWave: loosely a variant of a heaving device array. The working principles of this device are unique, but share some common features of the F-HBA device.
- Waveswing: heaving device, like the Bref-HB device
- Oscilla: heaving device, like the F-2HB device
- RTI: floating OWSC (oscillating wave surge converter – essentially rotation), like the F-3OF device.
- Sea Potential: heaving device, like the F-2HB device
- Harvest: floating OWSC (oscillating wave surge converter – essentially rotation), like the F-3OF device.

5. Results & discussion

In this section, values for the capture width ratio, the four metrics from Babarit et al. [5], and the WEPrize ACE metric are presented for the devices of the top seven WEPrize teams and the five deep water devices from [5]. The HPQ metrics, which are only available for the top four WEPrize teams that surpassed the ACE threshold, are also discussed. The section concludes with a discussion on the applicability of the ACE metric and recommendations for modifying it in future work. It

Table 2
Scaling factors for European sites in [5].

Sea State	T_P	H_S	Scaling Factors for Each Climate				
	(s)	(m)	SEM-REV	EMEC	Yeu	Lisboa	Belmullet
IWS 1	7.31	2.34	0.045	0.188	0.244	0.084	0.067
IWS 2	9.86	2.64	0.120	0.281	0.411	0.383	0.401
IWS 3	11.52	5.36	0.008	0.042	0.038	0.042	0.273
IWS 4	12.71	2.06	0.220	0.032	0.146	0.331	0.312
IWS 5	15.23	5.84	0.010	0.019	0.002	0.022	0.093
IWS 6	16.50	3.26	0.035	0.002	0.012	0.078	0.005
			Average Annual Wave Energy Flux (CP_j, kW/m)				
			14.8	21.8	26.8	37.5	80.6

should be kept in mind that LCOE is the most comprehensive metric for the market application at hand. Each of the metrics discussed in this paper attempt to provide performance information about a device in a much simpler way than calculating LCOE. These metrics are listed in order of complexity, the simplest being capture width ratio, then the four metrics from [5] that include a proxy of a portion of capital expenditure, the ACE which uses a simplified value of the structural cost of the device, and HPQ which attempts to add additional factors to ACE to account for missing pieces of the total cost.

5.1. Capture width ratio

The capture width ratio is a measure of the hydrodynamic efficiency of a device (in terms of energy capture not cost performance). The average CWR of the WEPrize devices is listed in Table 3. Fig. 2 shows the average CWR of the top six WEPrize team devices along with the devices in (for clarity the Harvest device is not shown due to its large diameter). For the WEPrize devices, the capture width is taken as the Average Climate Capture Width (ACCW) at the climates used for the WEPrize. The characteristic device diameter and CWR for the top seven teams are shown in Table 3. The characteristic diameter is calculated as in Babarit [6]:

$$B = \sqrt{\frac{4\,A_w}{\pi}} \tag{3}$$

where A_w is the device's maximum horizontal cross-sectional area and B is taken as its characteristic, or equivalent, diameter for calculating its capture width. Eq. (3) reduces to the diameter of a circle when the device is a circular shape (e.g., vertical circular cylinder or hemisphere).

The measured capture widths for AquaHarmonics and CalWave, the first and second place winners respectively, were somewhat higher than for Waveswing, the third-place team. Most devices in Fig. 2 with a CWR above 30% are fixed bottom deployed in shallow water. Fixed bottom devices may be difficult to deploy on the West Coast of the U.S. due to the likelihood of scouring, which may make them difficult to permit due to other competing uses and environmental restrictions. As a result, large array deployments may not be permissible, which is why they were not considered for WEPrize. However, near shore, fixed bottom surge wave converters may have a significant advantage in smaller, high energy cost niche markets, because their hydrodynamic efficiency is much higher, and the cable cost is much lower, even though the wave climate near shore is less energetic. It is clear from the data in Babarit [6] (and shown in Fig. 2) that fixed oscillating wave surge converters (OWSC, essentially rotating/oscillating devices like a flap) are very efficient (hence the high CWR), however, deep-water devices such as floating OWSCs (blue triangles) are not nearly as efficient because the reaction body is not fixed. The WEPrize required deep-water devices, so it is not expected that the CWR would be as high as bottom-fixed devices.

Fig. 3 shows the top six WEPrize CWRs with the three DOE Reference Model (RM) [7] WEC devices (RM3: point absorber, RM5: oscillating surge WEC, RM6: oscillating water column). The RMs were used to determine the threshold for the ACE metric in the WEPrize. CalWave is the only WEPrize device that has a larger average CWR than all three of the WEC Reference Models.

The CWR for the WEPrize devices at the European climates used in [5] is shown for comparison in Table 3 and is calculated as the ACCW using the scaling factors in Table 2. The CWR values at the European climates are within 1% of the CWR values at the WEPrize climates for all devices except Calwave, in which the difference was slightly larger (< 3%). The two larger sea states, IWS 3 and IWS 5 (see Table 1) have low scaling factors for all the WEPrize climates, however they become more significant for the Belmullet site, which has a much larger wave resource than any others considered (Table 2). These two sea states could be considered on the upper edge of operational conditions (closer to survival cases at most sites), under which teams may have limited their device motion to avoid damage. Calwave's capture widths for IWS 3 and IWS 5, although similar to other teams, is much lower compared to their performance in other sea states; so larger weighting at Belmullet has a bigger impact on their overall CWR. However, all teams had a difference of less than 3% in CWR and, therefore, as Babarit et al. [5] found, the capture width ratio is relatively insensitive to the climate.

5.2. Performance metrics based on absorbed energy and cost proxies

The four metrics defined in Babarit et al. [5] and calculated for the WEPrize devices are shown in Fig. 4 for both the U.S. and European climates. These four metrics, mentioned earlier, include (1) mean annual absorbed power, and absorbed energy per (2) characteristic mass, (3) wetted surface area, (4) root mean square PTO force. As expected, the mean annual absorbed power depends on the wave resource at each of the individual sites; the wave resource at the U.S. sites was given in Table 1 and the resource for the European sites is given in Table 2. The European sites in Table 2 vary more widely in their resource by design (the intention of Babarit et al. [5] was to test the performance at varying sites). Whereas the WEPrize targeted climates of likely deployment in the United States, which have similar resource (except Hawaii, which is lower).

The absorbed energy per characteristic mass (the second row of plots in Fig. 4), only includes the load bearing structure and it highlights the differences in material choices for the top three WEPrize teams. Waveswing was one of the only devices that is made primarily from fiberglass and not from steel, resulting in a much lower mass value. Waveswing is also a small device (characteristic diameter of 4 m), and even though its mean annual absorbed power is very small, its small mass allows it to score well using this metric.

The absorbed energy per wetted surface area ranking of the WEPrize teams (the third row of plots in Fig. 4), is similar to their final WEPrize ranking based on the HPQ. (For reference, the ACE and HPQ scores of the WEPrize teams are shown in Figs. 8–10, and will be discussed in the next subsection.) Finally, only four teams had PTO force measured (rather than torque), and Waveswing has the highest values of absorbed energy per root mean square PTO force.

Fig. 5 similarly shows the devices in Babarit et al. [5] for both the U.S. climates used for ACE, and the five European climates. Note that the performance data from the devices in [5] came from numerical modeling, while the data from the WEPrize is from 1/20 scale tank testing scaled up to full scale. Bref-HB is a very small device (based on the Seabased WEC under development in Sweden), rated at 10 kW. Therefore, the mean annual absorbed power is much lower than the other 4 devices, however it compares more closely on the other three metrics. For the absorbed energy per characteristic mass metric, this is in part because the foundation mass (which was 20 Mg) was removed to be consistent with the other devices, and would have been a large

Table 3
Capture width ratio for the top seven WEPrize teams.

Team	Characteristic diameter (m)	CWR at WEPrize climates	CWR at European climates in [5]
AquaHarmonics	15	23.2%	23.9%
CalWave	34.8	33.4%	30.7%
Waveswing	4	9.6%	9.4%
Oscilla	29.6	18.3%	17.8%
Sea Potential all PTOs	26	13.4%	13.0%
RTI	28	12.8%	12.6%
Sea Potential	26	7.8%	7.6%
Harvest	108.6	4.1%	3.7%

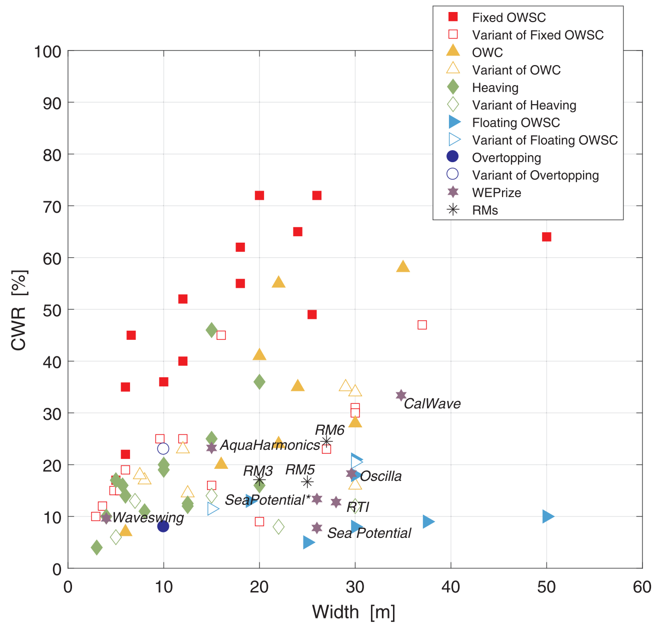

Fig. 2. Capture width ratio percentage plotted against device width for the top five WEPrize teams, the WEC reference models, and the database values in Babarit [6].

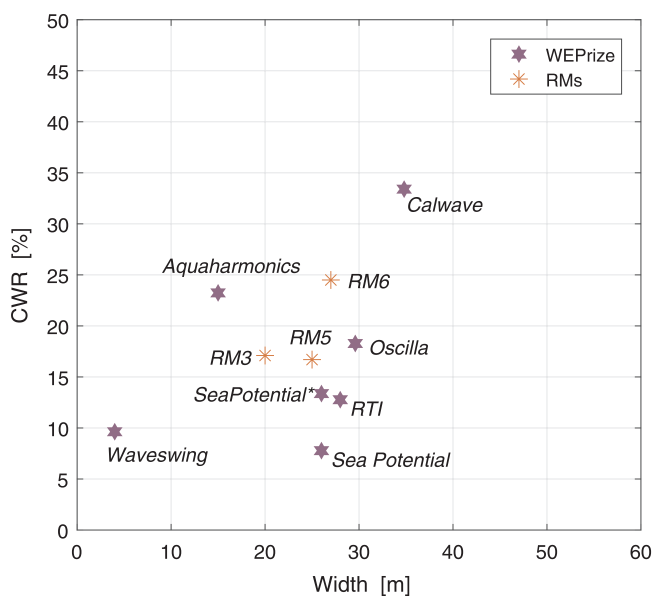

Fig. 3. Capture width ratio percentage plotted against device width for the top six WEPrize teams and the DOE WEC reference models (RM3: point absorber, RM5: oscillating surge WEC, RM6: oscillating water column). Note that Harvest is not shown for clarity because the device width is so large (see Table 3). SeaPotential* (with an asterisk) represents Sea Potential's results with all three PTOs included.

addition to the 11 Mg for the rest of the structure.

For ease of visual comparison, the four metrics for the WEPrize and Babarit et al. [5] devices are also shown in one plot at the U.S. climates in Fig. 6 and at the European climates in Fig. 7.

5.3. ACE

The ACE values of both the seven WEPrize teams and the five devices from in Babarit et al. [5] are presented in Fig. 8. In the WEPrize, ACE values were presented as a composite value for seven geographic areas of Northwestern Pacific waters, which is the first column for each device in the top plot of Fig. 8. The composite value for the five European sites is in the first column for each device in the bottom plot of Fig. 8. In this work, we expand on what was done for the WEPrize and separately present the ACE for the seven individual Northwestern Pacific sites and the five European sites to show the influence of location (wave resource) on ACE. For the Northwestern Pacific, devices tend to have similar ACE values except at Hawaii where most WEPrize teams have higher values. This result is because at Hawaii, IWS1 and IWS2 had large scaling factors (weighted higher), and devices from both WEPrize and Babarit et al. [5] tended to have higher capture efficiency for these sea states. While ACE scores varied between devices at the five European sites, the ACE scores for each individual climate showed little variation for the most part, even though site conditions varied widely. However, Calwave, Harvest, and Bref-HB had much lower ACE scores at Belmullet. The overall wave resource is much higher at Belmullet than any other site considered in this study, which results in an increased value of total absorbed energy, but a lower capture width due to the large scaling factors for large (bordering extreme) sea states, which devices are not typically designed to perform optimally at, and the denominator of CWR being so large (80.6 kW/m).

Only one of the deep-water devices from [5], Bref-HB, exceeded the ACE threshold. It was known during the development of the ACE metric that a very small device could have a high ACE value, but would ultimately have a very high LCOE when deployed in large arrays for bulk power generation. Thus, the small sizes of Bref-HB and Waveswing put them in another category where the ACE value, as currently defined, is not necessary applicable and should not be used as a sole means of comparison with the larger devices considered in this study. This is because, for small converters, the LCOE for a wave farm array is unlikely to be dominated by the structural cost of device, as assumed when employing the ACE metric. Small converters will need to be installed in much larger arrays to achieve the equivalent energy production of larger devices, and therefore the LCOE is likely going to be dominated by installation and maintenance as well as the electrical cable costs for the interconnection of the larger number of devices needed to generate significant levels of power. This is discussed in more detail in the following Lessons Learned section.

5.4. Comparison of ACE values with other metrics considered

The ACE rankings for the WEPrize devices (Fig. 8) are quite different than the absorbed energy per characteristic mass, Figs. 6 and 7. Several points can explain this:

- the Waveswing device has a low mass, but its material was more expensive per unit mass, which is not accounted for with the absorbed energy per characteristic mass metric;
- the Oscilla device has a large mass, but most of it is concrete, which is much less expensive per unit mass than steel;
- the Sea Potential device is only composed of concrete, which is much less expensive per unit mass than steel.

The five Babarit et al. [5] devices (Fig. 6) have low values of absorbed energy per characteristic mass as well. However, one developer commented in the full report [14] that a significant amount of the device's dry mass is cheap stone material, and simply using mass may not be the best indicator for comparing concepts. Therefore, this metric may only be useful when comparing devices that use the same materials or materials with similar manufacturing costs, which is the reason the ACE metric was designed to account for the different material costs in the structure.

In contrast, the absorbed energy per wetted surface area follows the trend of ACE rankings well. The only obvious outlier is the Waveswing device which had the second highest ACE, but whose HPQ ranking was third and is expected to be a more accurate reflection of the techno-

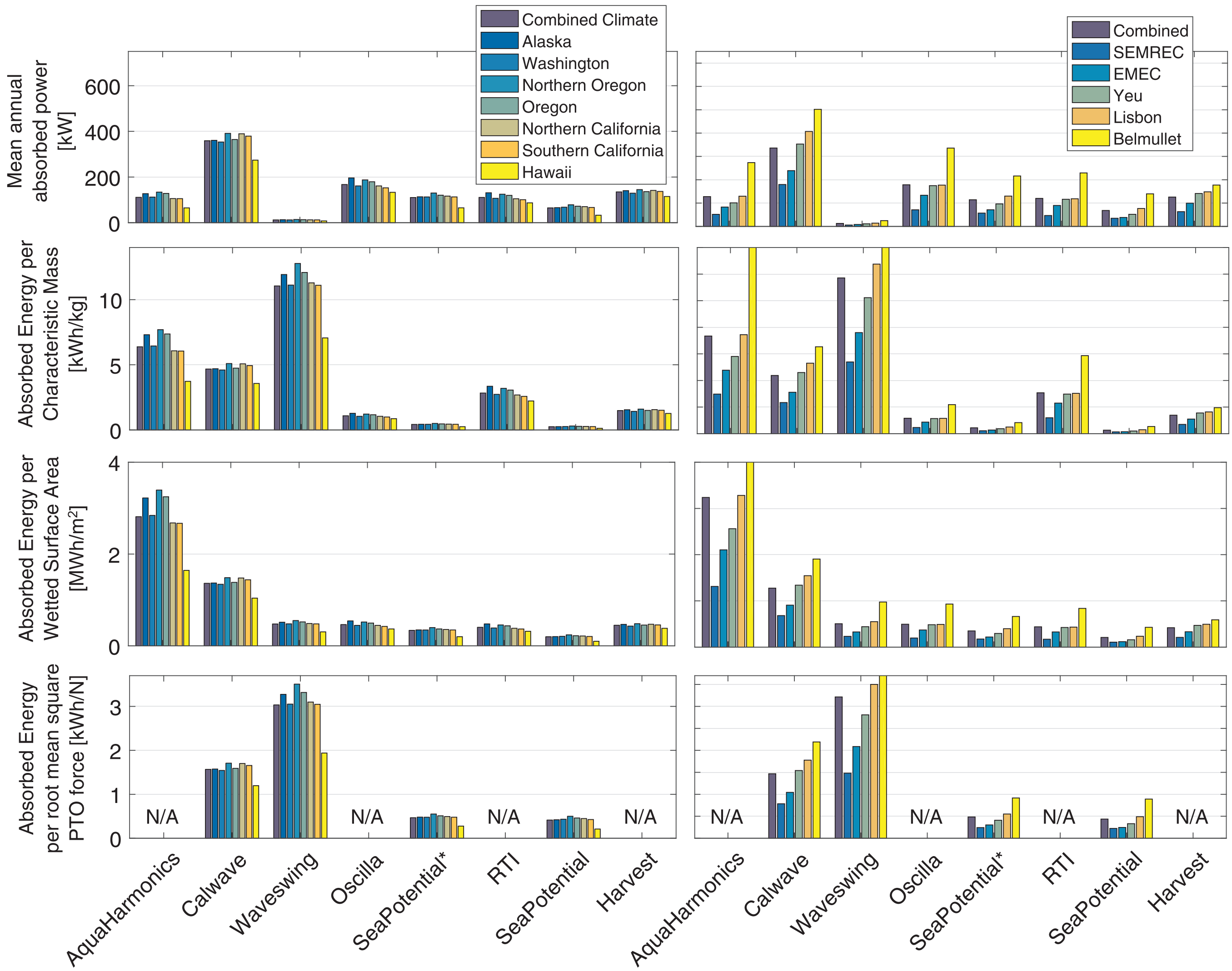

Fig. 4. Performance metrics in Babarit et al. [5] for the top 7 WEPrize devices, including Sea Potential with all PTOs (signified with an asterisk). The left subfigure presents results at the combined and individual WEPrize climates, and the right subfigure is at the five European climates in Babarit et al. [5]. Note that the mass does not include moorings or foundation. For clarity, the axis limits were set to encompass all but the Belmullet site, which has much larger wave resource (80.6 kW/m). The values of the data points at that site are shown in Fig. 7.

economic potential for similarly sized arrays compared to other devices. Absorbed energy per wetted surface area may appear to be a simpler proxy for ACE, however without directly relating to cost, a simpler metric may not be useful for projecting which technologies will have the lower LCOE. It is also recommended that modifications of ACE be investigated to account for costs in addition to the primary structure in as simple a manner as practical. Simple metrics, like unit energy capture per characteristic mass, will only be useful in situations where the underlying technology attributes and operational situations are comparable.

It is difficult to compare the rankings of the absorbed energy per root mean square PTO force to ACE since only four of the WEPrize devices and three of the five deep water devices in [5] have the needed data. More analysis of the type of PTO, rating, and cost as a portion of the Capital Expenditure of a WEC system would be needed to fully assess this metric, although it is expected to be important.

5.5. HPQ metrics

As described earlier, HPQ can be visualized as the ACE score weighted by the device performance during testing to account for several factors that impact LCOE but that are not captured in ACE. However, individual HPQ metrics used in the WEPrize (shown in Fig. 9) were only calculated for the four teams that surpassed the required WEPrize ACE threshold of 3 m/\$M. For the Prize, the HPQ multiplication factors described in Section 3 were determined by a relative comparison between the four technologies with input from judges, then multiplied by ACE to come up with the final HPQ scores that are plotted in Fig. 10. The individual metrics reveal intricacies of the technoeconomic potential of each device. The metrics that were statistically measured were normalized in order to compare devices of varying sizes and capacities. The intention was to consider the impact of these metrics assuming that each device would be deployed in an array of the same capacity. For example, the CalWave device is relatively large, rated at 800 kW according to their WEPrize technical submission, compared to the Waveswing device, which was rated at 65 kW. Therefore, to deploy an array of 10 MW, approximately 13 CalWave devices and approximately 154 Waveswing devices would be needed. The peak mooring forces, which will impact O&M, are even more important when many more mooring lines are deployed in an array. For this reason, the statistical peak of mooring forces (see [10,13] for formula), was normalized by both the number of lines per device, and the Average Climate Capture Width (ACCW), which represents the capacity of the device. Similarly, the statistical peak of watch circle and the end-

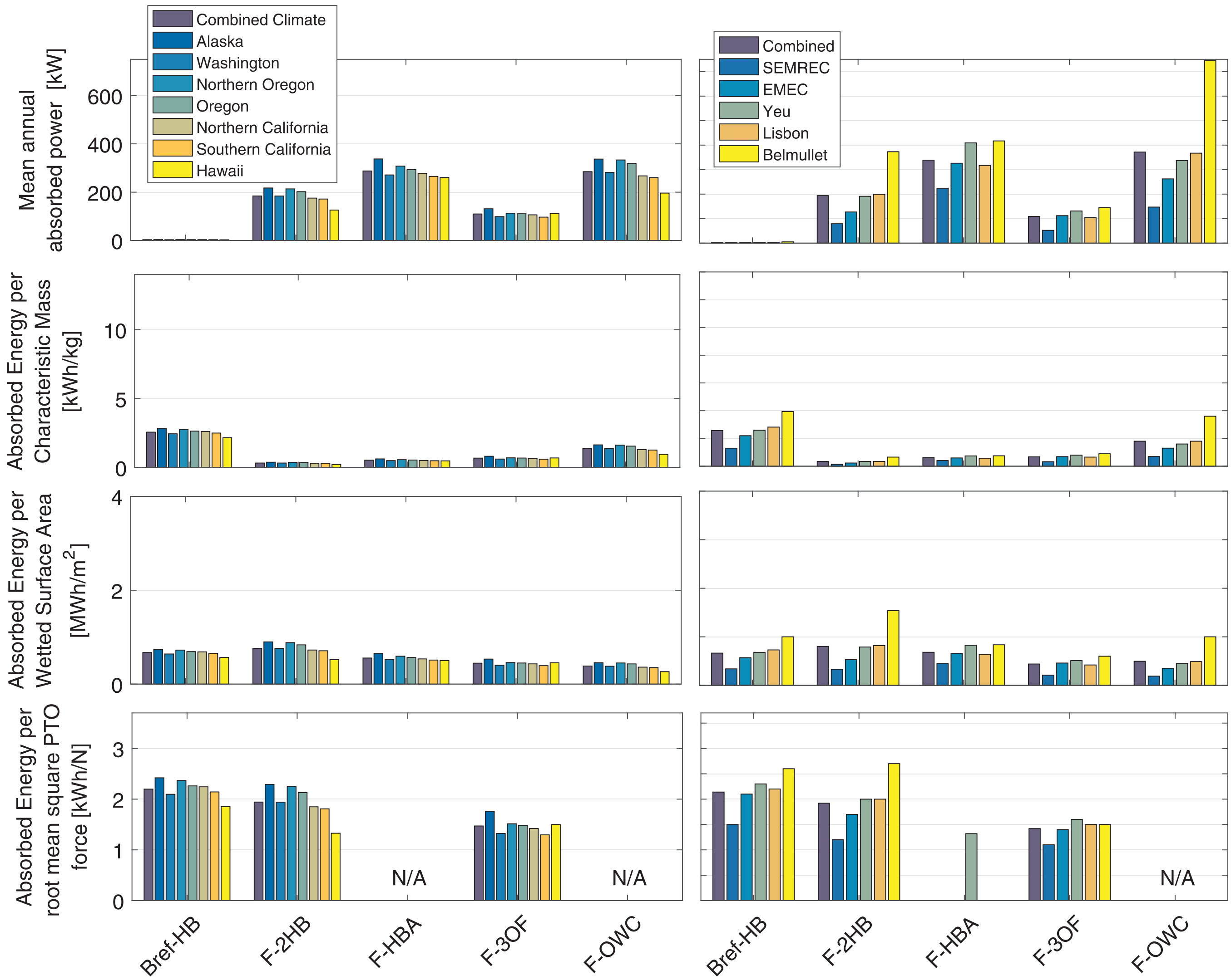

Fig. 5. Babarit et al. [5] devices at the US ACE climates and the five European climates. Note that the mass does not include moorings or foundation.

stop impact event values were normalized by ACCW. In Fig. 9, for the first four metrics (the top four figures), a higher value represents a negative techno economic impact, whereas in the fifth metric, ratio of absorbed power in realistic seas, a higher value represents a positive techno economic impact.

The peak to average power ratio is an important HPQ metric because it is a proxy for capacity factor, a common metric used in other power producing technologies, such as wind turbines. Capacity factor is the average electrical power generated divided by the rated peak power, so peak to average absorbed power is an inverse proxy (high capacity factor is favorable while low peak to average ratio is favorable). Although the WEPrize used representative PTOs, the actual PTO rating necessary for a device will depend on the peak power absorbed by the device, while the AEP is closely tied to the average power. Higher peaks either require a higher PTO rating (which is more expensive), or a loss of energy produced as well as higher forces on the selected PTO. Babarit et al. [5] studied the effect of limiting instantaneous power on the mean annual power absorption for some of the devices in their study. They found that the maximum PTO power could *at least* be limited down to about 20 times the mean power without significantly decreasing the mean annual output power. All four of the WEPrize teams that met the ACE threshold had a peak to average factor less than 10, with CalWave being the lowest at 5.2.

5.6. Lessons learned on the ACE metric

As stated in previous sections, the ACE metric was created with the intention to quickly assess low TRL WEC devices. The authors believe that the metric is successful in this regard, but is not without its limitations. Using the HPQ score attempted to address limitations of ACE, and include a measure of other techno economic factors.

One of the most significant assumptions that went into the creation of ACE is that the largest contributor to LCOE (37–52%) is the cost of the structure. This assumption is consistent across DOE efforts such as the MHK Reference Models [23], as well as international MHK cost reporting efforts [9,24]. However, with the variety of existing WEC devices, and with the intention of discovering new technologies, it is unrealistic to believe that the non-structural costs such as the Power Take Off, Mooring, Foundation, etc. would be equivalently weighted across all devices. Within the confines of existing state of the art WEC designs (e.g., hydraulic PTOs vs direct drive rotary generators), one can start to appreciate how the cost breakdown might vary significantly.

Lastly, as the ACE metric is defined it puts equal weight on structural cost and energy capture. However, if one were to follow the simplified LCOE equation it can be shown that weighting structural cost equally with energy production biases the results. The LCOE equations is shown below:

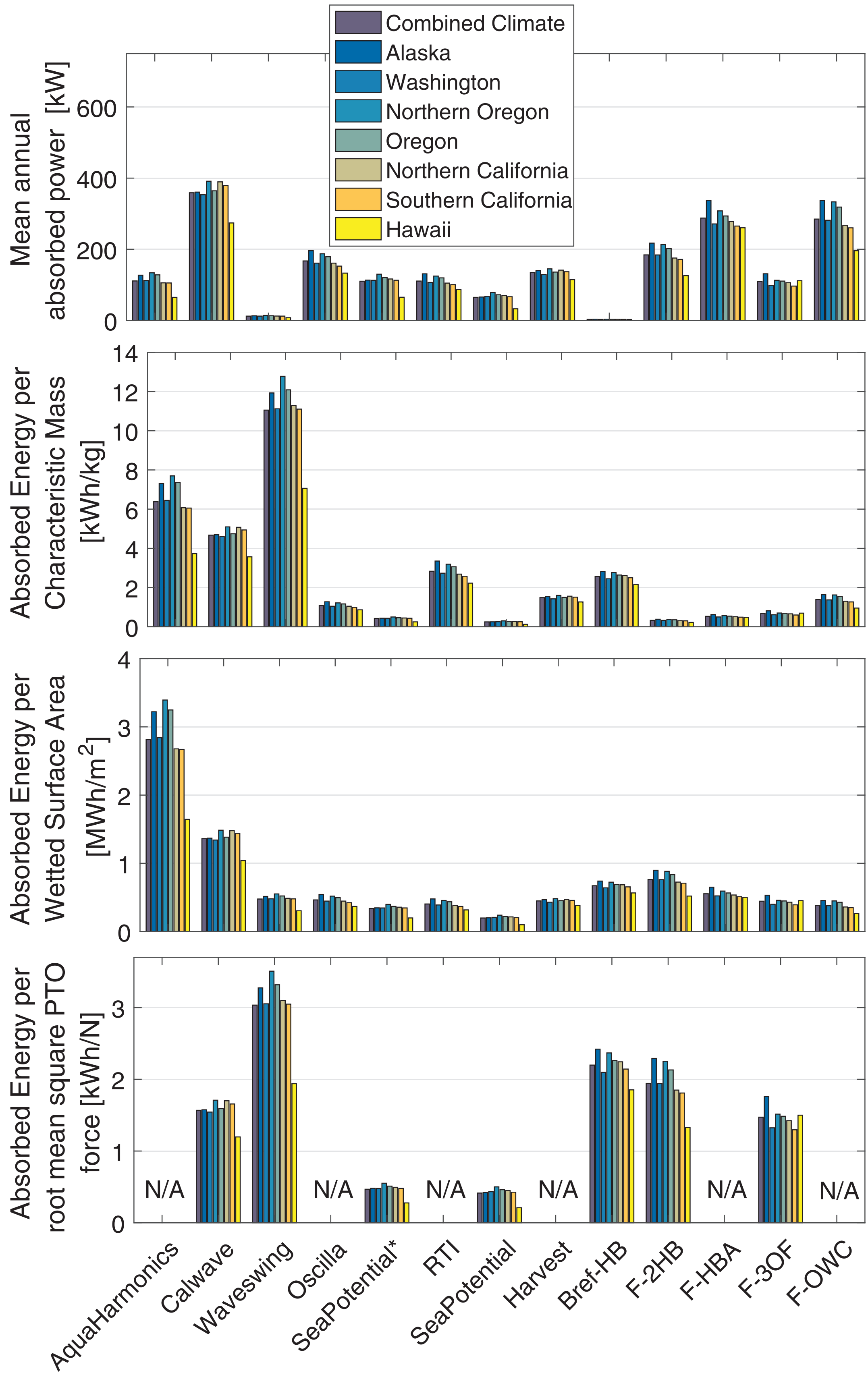

Fig. 6. Both sets of devices at US ACE climates. Note that the mass does not include moorings or foundation. The WEPrize devices include Sea Potential with all PTOs (signified with an asterisk).

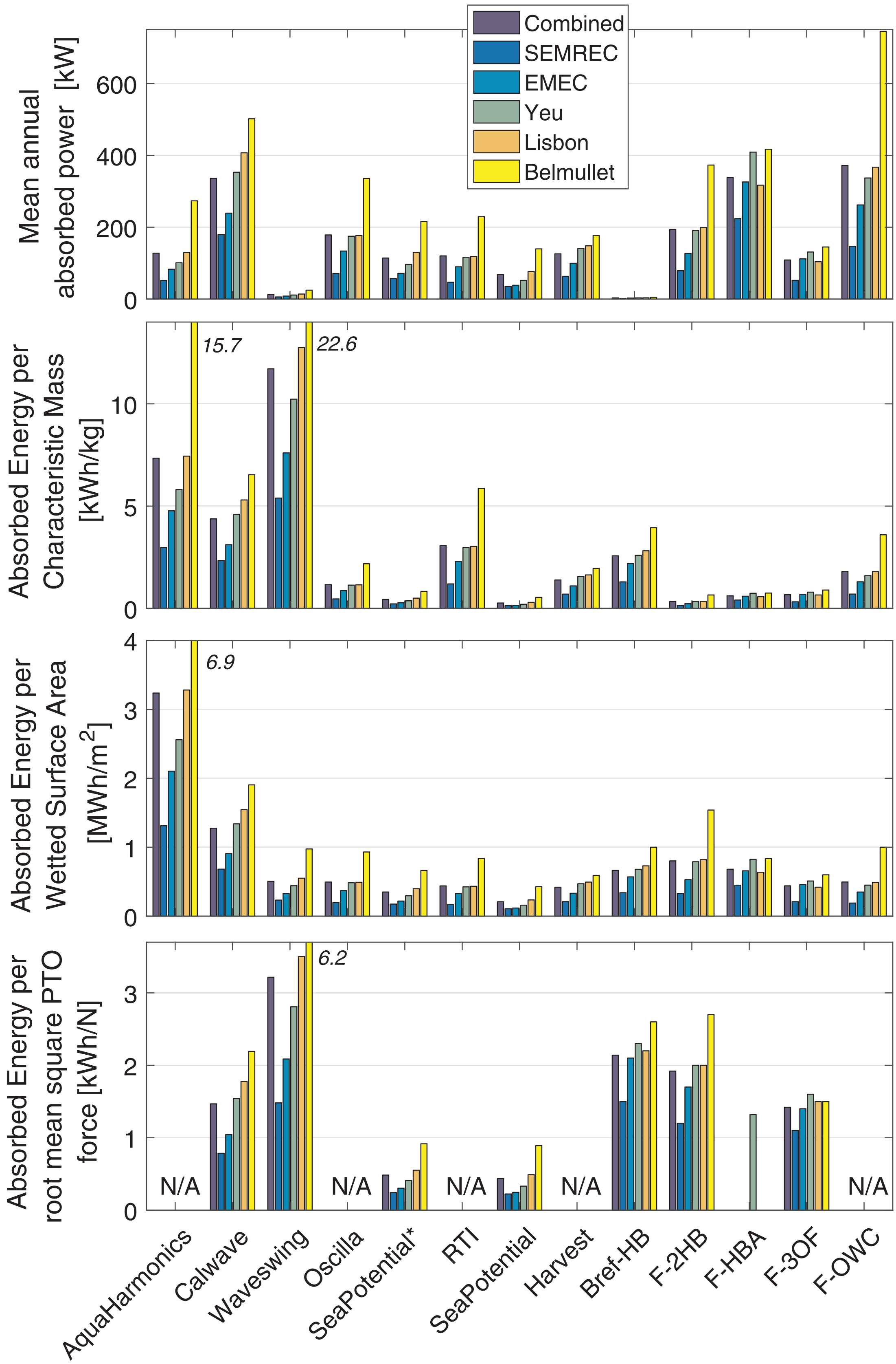

Fig. 7. Both sets of devices at the combined and individual five European climates from Babarit et al. [5]. Note that the mass does not include moorings or foundation. The WEPrize devices include Sea Potential with all PTOs (signified with an asterisk). To avoid skewing the view, the axis limits were chosen to enclose all data except Belmullet which has a much higher wave resource. The values of the bars that are cut off are shown in the figure.

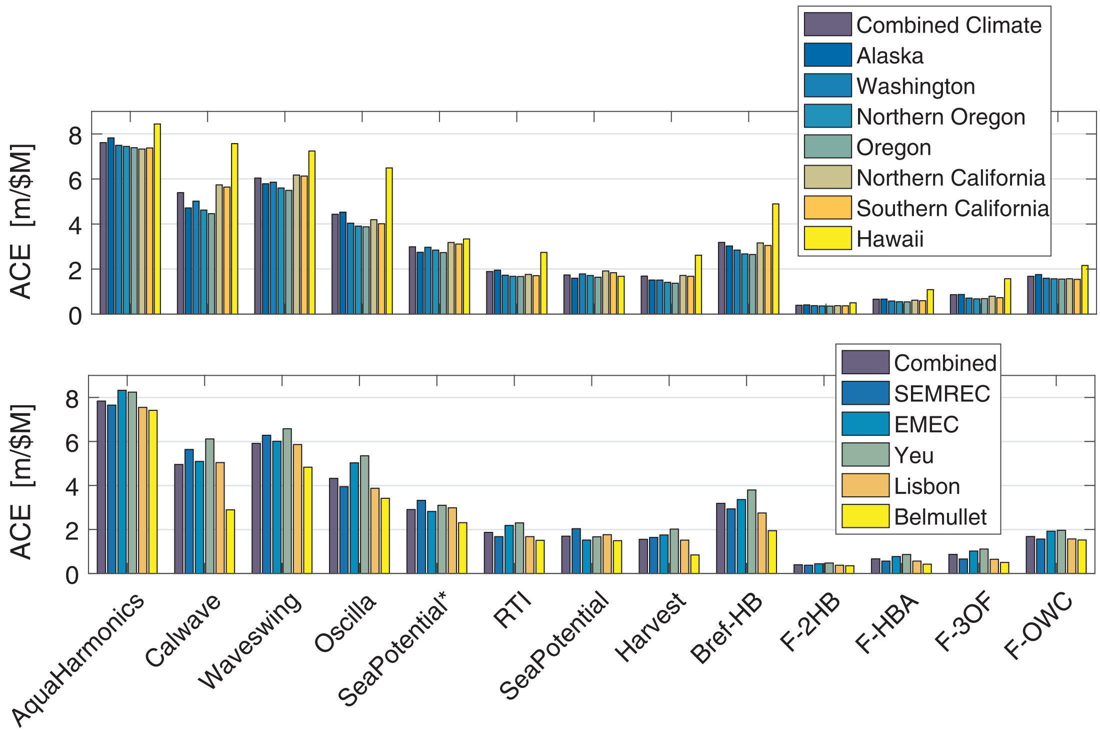

Fig. 8. ACE at the US climates and the five European climates, and each individual climate for the top seven WEPrize teams and the five deep water devices from Babarit et al. [5]. The WEPrize devices include Sea Potential with all PTOs (signified with an asterisk).

$$LCOE = \frac{(FCR*CapEx) + OpEx}{AEP} \tag{4}$$

where FCR represents a lumped financing term known as the fixed charge rate, CapEx includes all capital expenditures (structure, PTO, mooring, initial permitting, etc.), OpEx represents operational expenditures such as annual maintenance, and AEP represents the annual energy production delivered to the grid. Therefore, a 10% change in energy production will always result in a 10% change in LCOE, however a 10% change in structural cost depends on the FCR, OpEx, and what percentage of the CapEx comes from the structure. Therefore, the ACE metric is not a one-to-one representation of LCOE (e.g., doubling the ACE from the 2014 state of the art does not necessarily reflect a decrease in LCOE by one half). Additionally, ACCW does not account for PTO efficiency, creating a bias towards devices that have poor conversion efficiency but great power absorptions (i.e., a traditional wells turbine). The limitations to the ACE metric listed above are not a comprehensive list, however they give insight into what the most appropriate metric might be depending on what is being compared. Modifications could be made to the ACE equation to put more weight on ACCW, or less weight on the CCE, to create a closer approximation of the impact on LCOE. Another method would be to add an additional term to approximate the impact of the other system costs, both CapEx (PTO, Mooring, etc.) and OpEx. This is important because even if one were to somehow eliminate the structural cost from the WEC the LCOE would not go to zero. Using the DOE Reference Model 5 device, where the structure accounts for approximately 41% of the LCOE, zeroing out the structural cost would reduce the LCOE from $0.69/kWh to $0.41/kWh. However, the ACE value would go to infinity, giving false implications about the potential LCOE. If weighted appropriately, the ACE value could be used to budget the appropriate balance between energy improvements and structural cost reductions. Using the same estimates from RM5, the raw material cost (not including labor) for RM5 accounts for approximately $0.19/kWh. Therefore, significant improvements must be made to both the energy production and cost for the technology to be considered economically viable, and for this reason an augmented ACE metric may be the best choice when comparing the economic viability of different technologies.

6. Conclusions

The Wave Energy Prize performance data sets, which were collected using consistent methodologies and are of high quality, present a rare opportunity to compare, rank and benchmark the performance of different WEC device designs. Similar performance analyses by Babarit et al. [5] and Babarit [6] used WEC and PTO simulations to derive power performance metrics from which these comparisons were made. In the present study, values of performance metrics were used to compare and rank the performance of different WEC devices among the top seven WEPrize finalists, and WEC devices evaluated in the studies of [5,6], augmenting the databases, and allowing a reevaluation of trends established in these power performance benchmarking studies. A summary of results is given below.

- Out of the WEPrize devices, only the CalWave device has a higher CWR than all the reference models.
- The third place WEPrze team, Waveswing's device, has a CWR much lower than the first and second place teams.
- The annual absorbed energy differs greatly among devices, as found in [5].
- The average CWR for the various wave technologies changes by only a few percent in widely differing wave climates, as found in [5].
- Contrary to the result in [5], the absorbed energy per characteristic mass varies among devices, with the devices of the top three WEPrize teams obtaining a value much higher than 1 kWh/kg.
- The absorbed energy per wetted surface area values are consistent, except for the devices of the top two WEPrize teams, which have much higher values.
- Comparing values of absorbed energy per characteristic mass (and a related metric, power to weight ratio, PWR) is only recommended for devices of similar materials; for example, Waveswing had a low mass, but due to the more expensive material (filament wound FRP), it does not reflect the techno economic comparison with devices of

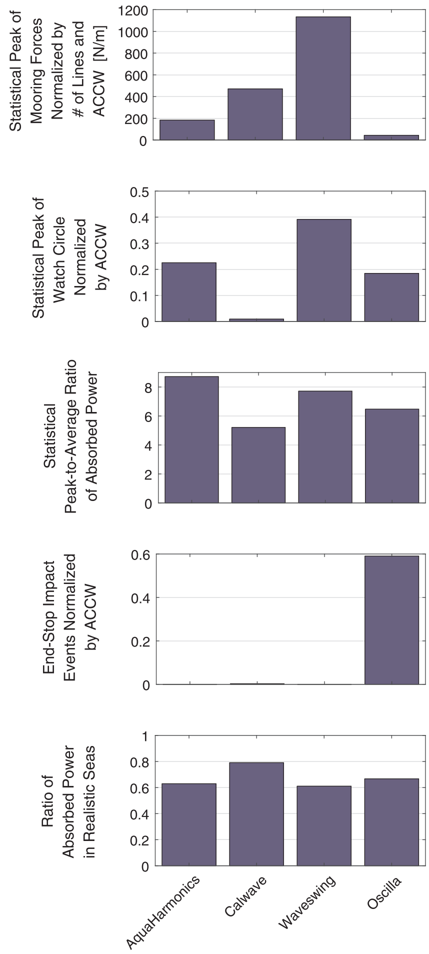

Fig. 9. HPQ metrics from the 1:20 testing for the top four WEPrize teams that surpassed the ACE threshold of 3 m/$M.

other more common materials, such as steel.

- Absorbed energy per surface area correlates well with the HPQ rankings for the WEPrize devices in this study; however, without directly relating to cost, this simpler metric may not be as useful.
- Although PTO force is important, the absorbed energy per root mean square PTO force metric could not be compared with all devices, limiting the evaluation of this metric. Analysis of the type of PTO, rating, and cost as a portion of the Capital Expenditure of a WEC system would be needed to fully assess this metric.
- To improve the ACE metric, we recommend augmenting the Characteristic Capital Expenditure (CCE) by including additional cost estimates to account for the other important system costs, such as the PTO, mooring, installation, and O&M costs.
- The HPQ metrics are also valuable for assessing the viability of a concept, because they provide a measure of very specific physical parameters that can be altered to increase the economic viability and reliability of a concept. For example, the peak to average power output is important, because the peak power determines the generator cost, while the average power determines the yearly revenue. Determining the optimal peak to average power ratio requires an economic tradeoff with a practical means of control. The way the HPQs were applied in the WEPrize cannot be widely used in their current form, because the values applied were judging inputs based on the relative performance of the four teams that met the ACE threshold.
- The devices of the three Wave Energy Prize winners, as well as Oscilla (the fourth-place team), performed consistently in terms of the ACE metric at both the U.S. and European climates. They also performed better than the devices modeled in Babarit et al. [5]. Unfortunately, the ACE is not a universal cost metric and it does not include several important attributes, like the moorings and the PTO, as noted above. However, the winners advanced the state of the art in terms of the ACE benchmark, which was the best available metric at the time of the WEPrize.

In summary, when only comparing a single device, smaller devices

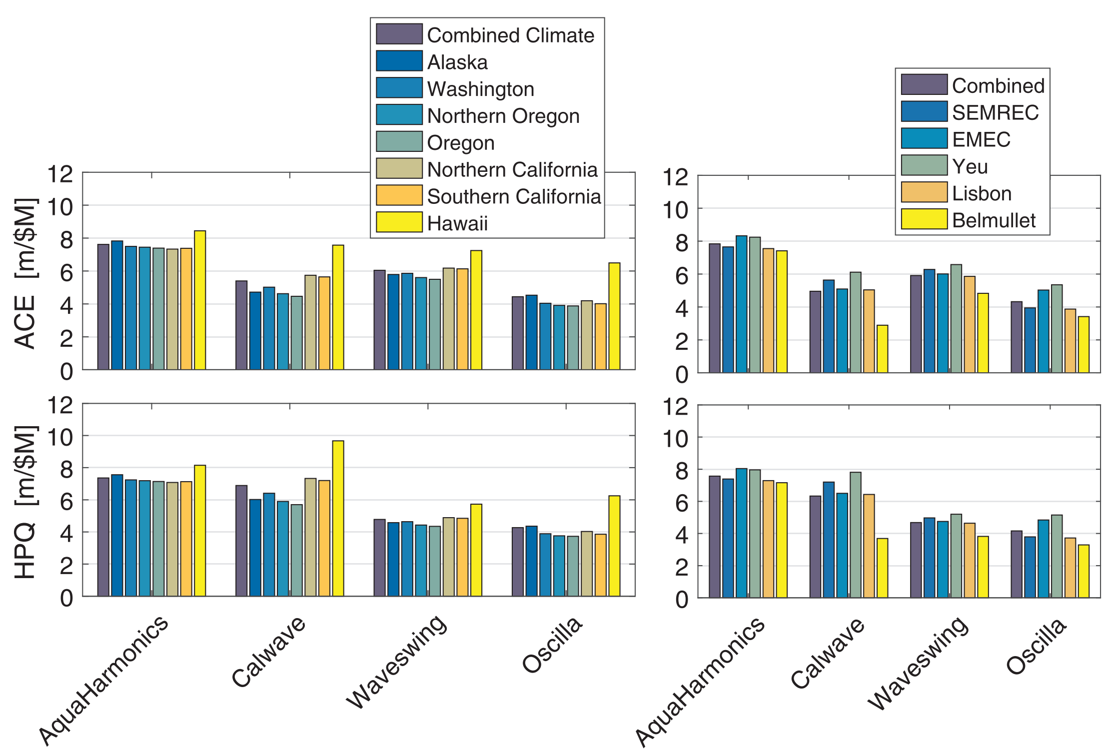

Fig. 10. ACE and HPQ at the US and European climates for the top four WEPrize teams that passed the ACE threshold of 3 m/$M.

will do better at metrics that compare energy absorbed to some proxy of the capital cost for one unit. However, when comparing devices in arrays at the same MW, O&M will become much more important. Therefore, it is recommended that the LCOE proxies considered in this study only be used for comparison of devices where structural material cost is clearly the dominant cost, and the number of devices needed to meet the application load be taken into consideration. The exploration of simple additions to develop an improved ACE metric is also recommended.

Acknowledgements

This work was funded by the U.S. Department of Energy's Water Power Technologies Office.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC under contract No., DE-AC36-08GO28308.

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Appendix A

WEPrize Device Performance Disclaimer: The Wave Energy Prize was a competition that had an aggressive schedule that moved teams from a notional concept to testing a 1:20 scale physical prototype in a period of just over a year. Unlike a conventional WEC technology development timeline that could take two or more years of full time effort to accomplish the same scope, these teams were working with limited budgets and many of the teams held full time jobs during the competition. Several teams also had new concepts for which scaling laws have not be developed and verified. Finally, for the 1:20 scale testing, each team only had one week to deploy, configure, troubleshoot, test and recover their WEC – there was very limited time to integrate data streams, troubleshoot and fix issues, tune controllers and conduct all the tests. Due to all of these constraints, several teams were not able to develop an appropriately scaled prototype and many teams had issues during testing (either in control, measurement, or device malfunction) that limited the test or degraded device performance. Thus, the performance of a concept measurement during the WEPrize does not necessarily reflect the full potential of the device. Given more time and budget, many teams could have improved performance – but that is not the nature of a prize.

References

[1] Huckerby J, Jeffrey H, de Andres A, Finlay L. An international vision for ocean energy. Version III. Published by the Ocean Energy Systems Technology Collaboration Programme; 2016. 〈www.ocean-energy-systems.org〉.

[2] Drew B, Plummer AR, Sahinkaya MN. A review of wave energy converter technology. Proc IMechE Part A: J Power Energy 2009;223(8):887–902.

[3] Uihlein A, Magagna D. Wave and tidal current energy – a review of the current state of research beyond technology. Renew Sustain Energy Rev 2016;2016(58):1070–81 [Available at: 〈https://www.sciencedirect.com/science/article/pii/S1364032115016676〉].

[4] Falcão AF de O. Wave energy utilization: a review of the technologies. Renew Sustain Energy Rev 2010;14(3):899–918 [Available at: 〈www.sciencedirect.com/science/article/pii/S1364032109002652〉].

[5] Babarit A, Hals J, Muliawan MJ, Kurniawan A, Moan T, Krokstad J. Numerical benchmarking study of a selection of wave energy converters. Renew Energy 2012;41:44–63.

[6] Babarit A. A database of capture width ratio of wave energy converters. Renew Energy 2015;80:610–28.

[7] Neary VS, Previsic M, Jepsen RA, Lawson MJ, Yu Y-H, Copping AE, Fontaine AA, Hallett KC, Murray DK. Methodology for design and economic analysis of marine energy conversion (MEC) technologies. Albuquerque, NM: Sandia National Laboratories; 2014. [SAND2014-9040].

[8] Previsic M, Bedard R, Hagerman G. E2I EPRI assessment: offshore wave energy conversion devices. E2I EPRI WP-004-US-Rev1. U.S.: Electricity Innovation Institute; 2004.

[9] International Levelised Cost of Energy for Ocean Energy Technologies. A report prepared on behalf of the IEA Technology Collaboration Programme for Ocean energy Systems (OES); May 2015. 〈https://www.ocean-energy-systems.org/oes-projects/task-7-cost-of-energy-assessment-for-wave-tidal-and-otec-at-an-international-level/#tab-results〉.

[10] EERE. Wave Energy Prize, U.S. Department of Energy [Online]; 2016. Available: 〈https://waveenergyprize.org/downloads/Wave_Energy_Prize_Rules_4_25_16_R3.pdf〉.

[11] Driscoll F, Newborn D, Quintero M, Gunawan B, Bull D, D Dallman A, Fingersh L, Ruehl, L. Wave Energy Prize testing and data analysis. In: Proceedings of the 12th European wave and tidal energy conference (EWTEC2017), Cork, Ireland.

[12] Hayden DD, Hoyt III JG, Carpenter S. Session 3 presentation - The Harold E. Saunders Maneuvering and Seakeeping (MASK) facility new directional wave-maker. Ocean Waves Workshop 2015, University of New Orleans. 〈http://scholarworks.uno.edu/oceanwaves/2015/Session3/3〉.

[13] Jenne S, Weber J, Thresher R, Driscoll F, Bull D, Dallman A, Neary V, Newborn D, Quintero M, LaBonte A, Karwat D. Methodology to determining the ACE Wave Energy Prize Metric. In: Proceedings of the 12th European wave and tidal energy conference (EWTEC 2017), Cork, Ireland.

[14] Babarit A, Hals J, Kurniawan A, Muliawan MJ, Moan T, Krokstad J. The NumWEC project: numerical estimation of energy delivery from a selection of wave energy converters - final report. Ecole Centrale de Nantes & Norges Teknisk-Naturvitenskapelige Universitet; 2011.

[15] Bull D, Dallman AR. Wave energy experimental sea state selection. In: Proceedings of the 36th International conference on ocean, offshore, and arctic engineering (OMAE2017-62675), ASME, Trondheim, Norway; 2017.

[16] Ricardo Detroit Technical Center. Wave Energy Prize − 1/20th Testing - AquaHarmonics [data set]; 2017. Retrieved from 〈https://mhkdr.openei.org/submissions/201〉.

[17] Ricardo Detroit Technical Center. Wave Energy Prize – 1/20th Testing - CalWave Power Technologies [data set]; 2017. Retrieved from 〈https://mhkdr.openei.org/submissions/205〉.

[18] Ricardo Detroit Technical Center. Wave Energy Prize – 1/20th Testing - Waveswing America [data set]; 2017. Retrieved from 〈https://mhkdr.openei.org/submissions/203〉.

[19] Ricardo Detroit Technical Center. Wave Energy Prize – 1/20th Testing - Oscilla Power [data set]; 2017. Retrieved from 〈https://mhkdr.openei.org/submissions/200〉.

[20] Ricardo Detroit Technical Center. Wave Energy Prize – 1/20th testing - RTI wave power [data set]; 2017. Retrieved from 〈https://mhkdr.openei.org/submissions/199〉.

[21] Ricardo Detroit Technical Center. Wave Energy Prize – 1/20th testing - sea potential [data set]; 2017. Retrieved from 〈https://mhkdr.openei.org/submissions/202〉.

[22] Ricardo Detroit Technical Center. Wave Energy Prize – 1/20th Testing - Harvest Wave Energy [data set]; 2017. Retrieved from 〈https://mhkdr.openei.org/submissions/206〉.

[23] Jenne D, Yu Y, Neary V. Levelized cost of energy analysis of marine and hydro-kinetic reference models. National Renewable Energy Laboratory; 2015. 〈http://www.nrel.gov/docs/fy15osti/64013.pdf〉.

[24] Ocean Energy: Cost of Energy and Cost Reduction Opportunities. SI Ocean, Strategic Initiative for Ocean Energy; 2013. 〈https://energiatalgud.ee/img_auth.php/1/10/SI_OCEAN._Ocean_Energy_-_Cost_of_Energy_and_Cost_Reduction._2013.pdf〉.