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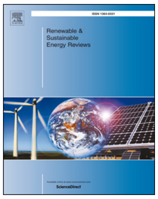

Evaluation of performance metrics for the Wave Energy Prize converters tested at 1/20th scale

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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

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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 lifecycle, 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.