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Wave Energy Prize Experimental Sea State Selection for the Benefit-to-Effort Threshold Metric, ACE

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1. INTRODUCTION

The Wave Energy Prize (WEPrize) was a public prize challenge sponsored by the U.S. Department of Energy (DOE)'s Water Power Program [1]. The prize was designed to increase the diversity of organizations involved in Wave Energy Converter (WEC) technology development, while motivating and inspiring existing stakeholders. The WEPrize was a three phase competition culminating in a test in the Maneuvering and Seakeeping (MASK) Basin at the Naval Surface Warfare Center (NSWC) Carderock Division in West Bethesda, Maryland. The selection of the winner was based on two metrics: the first a threshold value expressing the *benefit to effort ratio* (the ACE metric) and the second which included hydrodynamic performance-related quantities (the HPQ).

The ACE metric is a low TRL proxy for the levelized cost of energy. The two components that comprise the ratio ACE are:

- Average Climate Capture Width (ACCW) = a measure of the effectiveness of a WEC at absorbing power from the incident wave energy field in units of meters [m],
- Characteristic Capital Expenditure (CCE) = 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 is the ratio of ACCW to CCE with a threshold value of 3 m/$M.

Testing at the MASK basin occured using a Froude-scale factor of 20. The final selection of waves were required to be producible in the MASK Basin, which is 98.3 m by 61.7 m in area and 6.1 m deep at the testing location.

Due to the nature of the WEPrize, limited time was allotted to each contestant for testing and thus a limitation on the total sea states was required. However, the applicability of these sea states was required to encompass seven deployment locations representative of the United States West Coast and Hawaii. A cluster analysis was applied to scatter diagrams in order to determine a subset of sea states that could be scaled to find the average annual power flux at each wave climate for the ACE metric. These sea states offer a common experimental testing framework for performance in United States deployment climates. This paper covers the ACE sea states only, and the sea states necessary for HPQ are discussed in [2].

2. DEPLOYMENT LOCATIONS

The West Coast of the United States is the target area for large-scale commercial production of wave power, and is of primary importance. However, device performance in early market opportunity locations with high utility costs, such as Hawaii and Alaska, was also of interest to determine. Therefore, sea states that are representative of the U.S. Pacific West Coast and Hawaii wave climates were selected. Specific locations were chosen based on the desire to have a mixture of predominant incoming environments, good spatial distribution, at least seven years of data, and also locations that have been considered as probable for the development of WEC farms. The buoys used for data analysis are detailed in Table 1. Buoys near the 100 m contour line were most desirable but not available in all locations. All average annual power (AAP) flux values were calculated for a single depth of 122 m since each of the deployment locations were to be tested in the MASK basin (122 m is twenty times the testing depth in MASK for the Prize).

Sea state parameters reported by NDBC were used to analyze the wave climate at each buoy. The significant wave height reported by NDBC (and used here) is the average of the highest one-third of all the wave heights during a 20-minute sampling period. The peak period is the inverse of the frequency with maximum energy in the spectrum.

The scatter diagrams of H_s vs T_p for occurrence and percentage of total energy were calculated and are shown as subplots for Newport Oregon in Figure 1. The top subplot in Figure 1 shows the percent occurrence of each

Table 1: NDBC BUOYS CHOSEN FOR ANALYSIS. NOTE THAT ONLY PARAMETER DATA FROM NDBC WAS CONSIDERED TO KEEP A CONSISTENT FORMAT. (NO DATA FROM CDIP WAS USED.) POR STANDS FOR PERIOD OF RECORD, AS OF 2015.

NDBC #, Location	Depth	Years, POR	Coordinates	AAP Flux in 122 m depth
46083 Glacier Bay, AK	141.4 m	Parameters: 2002-2013, 12 yrs	58.237N 137.986W (58°14′13"N 137°59′8"W)	35.5 kW/m
46041 Aberdeen, WA	114.3 m	Parameters: 1988-present, 27 yrs	47.353N 124.731W (47°21′10"N 124°43′50"W)	32.7 kW/m
46029 Camp Rilea, OR	144.8 m	Parameters: 1985-present, 30 yrs	46.159N 124.514W (46°9′32"N 124°30′52"W)	39.3 kW/m
46050 Newport, OR	128 m	Parameters: 1992-present, 23 yrs	44.639N 124.534W (44°38′20"N 124°32′2"W)	37.9 kW/m
46013 Bodega, CA	116.4 m	Parameters: 1981-present, 34 yrs	38.242N 123.301W (38°14′31"N 123°18′2"W)	31.5 kW/m
46218 Lompoc, CA	549 m	Parameters: 2005-present, 10 yrs	34.458N 120.782W (34°27′29"N 120°46′56"W)	31.2 kW/m
51202 Oahu, HI	82 m	Parameters: 2005-present, 10 yrs	21.414N 157.679W (21°24′51"N 157°40′44"W)	16.8 kW/m

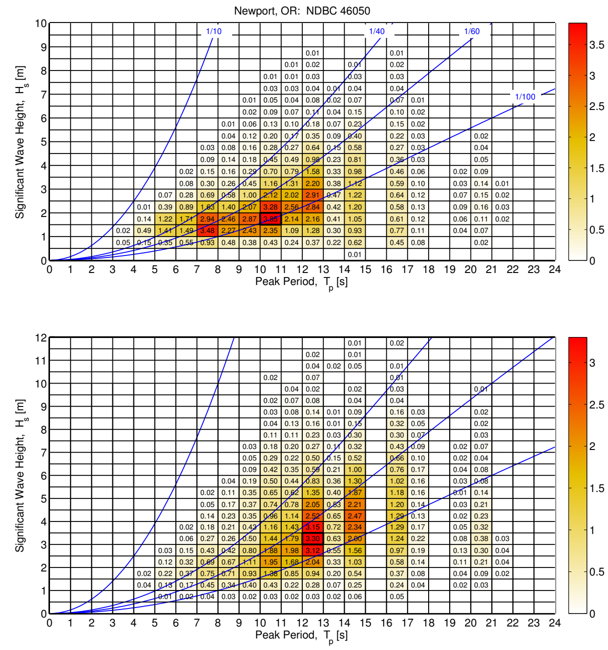

Figure 1: Occurence and energy occurence scatter diagrams for NDBC 46050, Newport Oregon.

binned sea state. Significant wave height is binned in 0.5 m intervals, and peak period is binned in 1 s intervals. Bulk steepness curves (H_s/λ, where λ is the wave length calculated using the dispersion relation with T_p) are shown as well. The most probable sea state is signified by a black box. The lower subplot in Figure 1 shows the percentage of total energy that each sea state contributes. The sea state contributing the most to total energy is signified by a black box.

There are empty bands of T_p in the JPDs, for example from $15\,\text{s} \leq T_p < 16\,\text{s}$, because some of the lower frequencies recorded by NDBC are uniformly spaced, which correspond to greater spaced peak periods. Although the frequencies recorded by NDBC changed over the years, some of the frequencies recorded by NDBC over the POR are 0.06 Hz, 0.0625 Hz, 0.0675 Hz which correspond to periods of 16.67 s, 16 s, 14.81 s. Therefore there is no data in the bin $15\,\text{s} \leq T_p < 16\,\text{s}$.

3. SEA STATE SELECTION: K-MEANS ALGORITHM

Following the work of [3] a cluster analysis was applied to scatter diagrams in order to determine a subset of sea states that could be scaled to find the average annual power flux. This subset is found via minimization of the squared Euclidian distance between each point and a cluster centroid. This k-means clustering procedure is a built-in MATLAB algorithm within the Statistics Toolbox; the user defines the number of clusters over which the optimization should take place. An iterative partitioning method optimizes the centroid of each cluster and the cluster size by minimizing the sum of point-to-centroid distances, summed over all k clusters. Hence, each sea state is assigned to an optimally determined cluster centroid that has the minimum point-to-centroid cluster distance.

The k-means clustering algorithm can be used on either the occurrence or energy occurrence scatter diagrams. The energy occurrence is of primary importance for WECs and therefore this analysis focuses on the application of k-means clustering on the energy occurrence scatter diagrams. Figure 2 shows the optimal assignments for six clusters when analyzing the energy occurrence scatter diagram for Newport, OR. The details of the cluster centroids and scalings are given in Table 2.

The goal of the clustering analysis is to obtain the average annual power flux for each deployment location using a small subset of the sea states that comprise the scatter diagram. As would be expected, the sum of all of the occurrences within the identified cluster boundaries to identify the initial scaling factor Ξ_{ini} for that cluster combined with the omnidirectional power fluxes results in incorrect average annual power fluxes for the deployment location. For example, the sum of the weighted power flux values using Ξ_{ini} results in an average annual power (AAP) flux of 99.5 kW/m. Therefore, the scaling for each cluster must be calculated in a distinct way such that the total occurence weighted power flux within that cluster is represented. In this

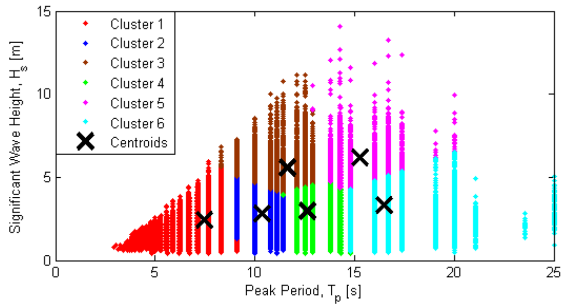

Figure 2: Clustering example using k-means for NDBC 46050, Newport, Oregon, using the energy occurrence scatter diagram. The average annual power (AAP) flux at the buoy's deployment depth is 37.8 kW/m.

method, the occurrence weighted power flux was calculated by summing the product of the probability of occurrence with the power flux for all data points within the cluster boundaries for each energy occurrence cluster. This value divided by the power flux of the centroid determines the correct scaling factor for the centroid. For example, Cluster 3 in Table 2 contributes a total of 5.56 kW/m of power flux to the average annual power flux of 37.8 kW/m. Given that this centroid's omnidirectional power flux is 162 kW/m this procedure then dictates that the adjusted scaling Ξ should be the ratio of these two values to obtain 0.034. These adjustments ensure that the average annual power flux would be obtained from the sum over all clusters of the power flux multiplied by their adjusted scaling factors.

Table 2: K-means cluster analysis on energy occurrence scatter diagram and subsequent adjustments to the scaling factors. The sum of the weighted power values using Ξ results in an AAP flux of 37.8 kW/m (the AAP flux at the buoy's depth as in Figure 2).

	T_p	H_s	Power Flux	Ξ_{ini}	Weighted Power $Flux_{ini}$	Ξ	Weighted Power Flux
	sec	m	kW/m	%	kW/m	%	kW/m
1	7.60	2.39	18.2	0.079	1.44	0.163	2.98
2	10.66	2.73	33.6	0.217	7.30	0.244	8.21
3	11.57	5.74	162.	0.147	23.8	0.034	5.56
4	13.32	3.23	60.5	0.293	17.7	0.183	11.1
5	15.19	6.09	251.	0.147	36.9	0.022	5.55
6	17.62	3.59	105.	0.117	12.3	0.042	4.41

Another important facet of this technique is that centroid location can be altered and the cluster to be associated with the newly altered centroid can be recalculated. The cluster points are again selected through minimization of the squared Euclidian distance using the built in MATLAB function *pdist2*. Hence, not only can the cluster centroids be assigned using the k-means algorithm, they can also be selected and the most optimal cluster can then be associated with them using the same squared Euclidian distance as the minimization parameter.

These two techniques, optimal assignment of the centroid and optimal assignment of the cluster given a centroid definition, will be used in the following sections to determine the single set of six sea states used to describe all seven deployment locations.

4. COALESCENCE OF DEPLOYMENT LOCATIONS

For the tank testing, a limited number of common sea states must be chosen and these should represent the wave climates at the seven selected sites. The common set of sea states can be given site-specific scaling factors in order to represent the climate at each site, including the distinct annual average power at each site.

The cluster analysis described above was used to find the optimal set of six sea states (or centroids in this method) for each deployment location using the energy occurrence scatter diagrams. This analysis revealed seven distinct optimizations as shown in Table 3, however one set of centroids was needed to represent all seven deployment locations. Coalescing of these sea states required multiple iterations to ensure that no individual sea state (or set of sea states) represented more than ∼30% of the annual average power flux, i.e. that the distribution of contribution to the average annual power flux was even as opposed to highly peaked towards individual sea states.

In the first iteration to coalesce the sea states, similar centroids among the buoys were averaged to find possible common centroids. This method was completed with the intent to minimize the standard deviations in the average and hence represent the commonalities; in some instances, outliers were removed to adhere to this goal. In addition, the wave tank is limited to maximum periods (at full scale) of about 16-17 s. Therefore, the peak period for the sixth common centroid was set given the tank limitations.

After this initial set of common centroids was found, small alterations were made to the centroid centers. Each of these alterations had a unique purpose: increasing spread between peak periods, achieving centroid centers on approximately constant bulk steepness lines, and to ensure that no centroid was dominate (in terms of its contribution to the average annual power flux at the deployment location) across multiple deployment locations. Centroids 3 & 4 were the targets of these iterations. The updated set of centroids are shown in Table 4.

Directionality of the sea states was also assessed and off-head waves were assigned to some of the six determined sea states for the ACE calculation. This is discussed in detail in [2]. Further details on the ACE metric and the calculation of the numerator, ACCW using the sea states selected in this paper, can be found in [4].

5. CONCLUSIONS

This paper discussed the methods and analysis behind the selection of the experimental ACE sea states for the WEPrize competition. Six sea states were chosen to represent seven distinct deployment climates of interest on the West Coast of the United States. The

Table 3: The six cluster centroids found using k-means clustering on the energy occurrence scatter diagram for each deployment location.

		1	2	3	4	5	6
Glacier Bay	T_p [s]	7.30	10.30	12.07	12.10	15.09	15.38
	H_s [m]	2.72	2.87	3.74	5.99	7.10	3.83
Aberdeen	T_p [s]	9.28	11.82	12.21	15.28	15.40	20.34
	H_s [m]	2.35	4.98	2.82	3.37	6.41	3.66
Camp Rilea	T_p [s]	9.76	11.59	13.51	13.76	16.81	17.43
	H_s [m]	2.48	4.75	3.27	6.69	6.37	3.18
Newport	T_p [s]	7.60	10.66	11.57	13.32	15.19	17.62
	H_s [m]	2.39	2.73	5.74	3.23	6.09	3.59
Bodega	T_p [s]	7.51	10.09	12.18	14.28	15.42	17.80
	H_s [m]	2.54	2.85	3.00	2.91	5.21	3.07
Lompoc	T_p [s]	7.74	9.86	12.40	15.03	15.42	18.94
	H_s [m]	2.37	2.83	2.93	4.39	2.32	3.31
Oahu	T_p [s]	6.21	7.50	9.10	11.13	12.95	15.59
	H_s [m]	1.87	2.12	2.34	2.49	2.36	2.44

k-means clustering method was used to identify the best cluster definitions from the energy occurrence scatter diagrams, and the same minimization technique (squared Euclidian distance) was then used to define the cluster boundaries for the six common sea states to all seven deployment locations. Scaling factors (Ξ) were determined such that the scaled centroids would sum to the expected average annual power flux (in 122 m water depth) for each deployment location. These sea states, along with the HPQ sea states described in [2], offer a common experimental testing platform for performance in United States deployment climates.

6. ACKNOWLEDGEMENTS

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Table 4: The final set of centroids, and the associated power, steepness, adjusted weights, weighted power, and percent of average annual power.

	T_p	H_s	**Power Flux**	**Steep**$^{-1}$	Ξ	**Weighted Power Flux**	**Contrib. to AAP Flux**
	s	**m**	**kW/m**	λ_{T_p}/H_s		**kW/m**	**%**
Glacier Bay, AK	7.31	2.34	16.7	35.6	0.243	4.07	11
	9.86	2.64	29.0	57.5	0.332	9.62	27
	11.52	5.36	141.1	38.6	0.075	10.59	30
	12.71	2.05	23.1	122.4	0.200	4.61	13
	15.23	5.84	233.5	60.4	0.024	5.61	16
	16.50	3.25	79.8	124.9	0.012	1.00	3
						35.5	
Aberdeen, WA	7.31	2.34	16.7	35.6	0.137	2.29	7
	9.86	2.64	29.0	57.5	0.277	8.03	25
	11.52	5.36	141.1	38.6	0.041	5.82	18
	12.71	2.05	23.1	122.4	0.338	7.80	24
	15.23	5.84	233.5	60.4	0.022	5.19	16
	16.50	3.25	79.8	124.9	0.045	3.56	11
						32.7	
Camp Rilea, OR	7.31	2.34	16.7	35.6	0.155	2.60	7
	9.86	2.64	29.0	57.5	0.307	8.88	23
	11.52	5.36	141.1	38.6	0.056	7.88	20
	12.71	2.05	23.1	122.4	0.344	7.94	20
	15.23	5.84	233.5	60.4	0.037	8.63	22
	16.50	3.25	79.8	124.9	0.042	3.35	9
						39.3	
Newport, OR	7.31	2.34	16.7	35.6	0.175	2.93	8
	9.86	2.64	29.0	57.5	0.268	7.77	20
	11.52	5.36	141.1	38.6	0.058	8.12	21
	12.71	2.05	23.1	122.4	0.295	6.80	18
	15.23	5.84	233.5	60.4	0.034	8.00	21
	16.50	3.25	79.8	124.9	0.054	4.29	11
						37.9	
Bodega, CA	7.31	2.34	16.7	35.6	0.207	3.47	11
	9.86	2.64	29.0	57.5	0.230	6.67	21
	11.52	5.36	141.1	38.6	0.012	1.64	5
	12.71	2.05	23.1	122.4	0.466	10.76	34
	15.23	5.84	233.5	60.4	0.016	3.85	12
	16.50	3.25	79.8	124.9	0.064	5.08	16
						31.5	
Lompoc, CA	7.31	2.34	16.7	35.6	0.152	2.54	8
	9.86	2.64	29.0	57.5	0.270	7.81	25
	11.52	5.36	141.1	38.6	0.014	2.00	6
	12.71	2.05	23.1	122.4	0.391	9.03	29
	15.23	5.84	233.5	60.4	0.010	2.24	7
	16.50	3.25	79.8	124.9	0.095	7.61	24
						31.2	
Oahu, HI	7.31	2.34	16.7	35.6	0.328	5.49	33
	9.86	2.64	29.0	57.5	0.245	7.09	42
	11.52	5.36	141.1	38.6	0.001	0.10	1
	12.71	2.05	23.1	122.4	0.133	3.07	18
	15.23	5.84	233.5	60.4	0.000	0.03	0
	16.50	3.25	79.8	124.9	0.013	1.06	6
						16.8	