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Assessment of Wave Energy Resources and Factors Affecting Conversion

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Abstract

The wave energy resource for U.S. coastal regions has been estimated at approximately 1,200 TWh/yr (EPRI 2011). The magnitude is comparable to the natural gas and coal energy generation. Although the wave energy industry is relatively new from a commercial perspective, wave energy conversion (WEC) technology is developing at an increasing pace. Ramping up to commercial scale deployment of WEC arrays requires demonstration of performance that is economically competitive with other energy generation methods. The International Electrotechnical Commission has provided technical specifications for developing wave energy resource assessments and characterizations, but it is ultimately up to developers to create pathways for making a specific site competitive.

The present study uses example sites to evaluate the annual energy production using different wave energy conversion strategies and examines pathways available to make WEC deployments competitive. The wave energy resource is evaluated for sites along the U.S. coast and combinations of wave modeling and basic resource assessments determine factors affecting the cost of energy at these sites. The results of this study advance the understanding of wave resource and WEC device assessment required to evaluate commercial-scale deployments.

Introduction

The theoretically recoverable wave energy along the U.S. coast has been estimated at approximately 1,200 TWh/yr by EPRI (2011) which could help in providing a substantial resource for the U.S energy production fleet. While wave energy converter (WEC) technologies are still in their development phases, the technology is advancing rapidly and scaled versions of commercial devices are currently being tested. Test facilities such the Pacific Marine Energy Center Test Site, the Hawaii Wave Energy Test Site, the United Kingdom Wave Hub (OES 2017) and programs like the U.S. Department of Energy Wave Energy Prize are fueling the present technology advancement. However, before WEC projects advance to commercially competitive scales, the energy production and economic performance must be critically evaluated.

Previous work has identified multiple methodologies and technologies for reducing the levelized cost of energy (LCOE) for wave energy. The most promising methods identified have included improved power conversion, advanced controls, and device design optimizations (OES 2015; Sandia 2014). While reduced capital and operational expenditures (CAPEX and OPEX) are important targets for cost reduction, some of

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the largest reductions in LCOE are through strategies that increase energy productivity (Teillant et al. 2012; Sandia 2014; OES 2015). Generally, increasing the annual energy production (AEP) is the shortest pathway to reducing LCOE for wave energy (Sandia 2014; Chang et al. 2018).

For specific locations, wave resource estimates provide the foundation of an AEP assessment by a developer for determining if a project is feasible for providing power to the electrical grid. An overall site assessment involves a full cost-benefit analysis including project costs, utility costing, and myriad other factors, but the wave resource is foundational in the project assessment (Robertson 2017; Sandia 2014). The goal of a site resource assessment is to determine the AEP for a specific site and WEC deployment strategy at that site. The goals of this study are to illustrate an overall evaluation of the energy produced by a WEC or WEC array and examine the potential pathways to increased AEP. The pathways evaluated include site selection, WEC characteristics, and the WEC array configuration. By using a combination of analytic, empirical, and numerical tools, the various pathways can be examined and assessed to assist in guiding future developments.

Methodology

Assessing the energy production at a wave energy site involves evaluation of the marine environment (e.g., waves), the WEC deployment strategy, and the operational model. Fundamental to the initiation of a site development is assessment of the wave energy resource. The wave energy resource is the amount of energy available for extraction from surface waves in the ocean. Using the available resource allows for strategies for energy capture to be evaluated. Hence, the methodology is to assess the available resource for four sites and then evaluate the strategies for power capture.

Wave Power

As waves propagate, wave energy is transported with the velocity of that wave. The transport rate of wave energy parallel to a wave crest is the wave energy flux (also referred to as wave power). The wave height and wave period are the determinants of the wave power. Wave power varies as the square of the significant wave height (H_s^2), linearly with the energy period T_e, and is expressed in watts of power per unit of wave crest width (W/m). Unique to wave energy is that the resource is a bivariate function of wave height and period when compared to solar or wind resources, which generally depend upon one metric for resource determination (e.g., irradiance, wind speed). A theoretical wave power resource (P), which is the energy contained in the entire resource, can be computed by

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e$$

where H_s and T_e are the significant wave height and energy period, and and g are the seawater density and acceleration due to gravity. Using either a continuous wave record or a joint probability distribution (JPD) of wave heights and periods at a specific location, the available power can be calculated from measured or modeled data. Figure 1 shows a sample JPD of significant wave height and period that can be used to calculate a theoretical power resource for a site.

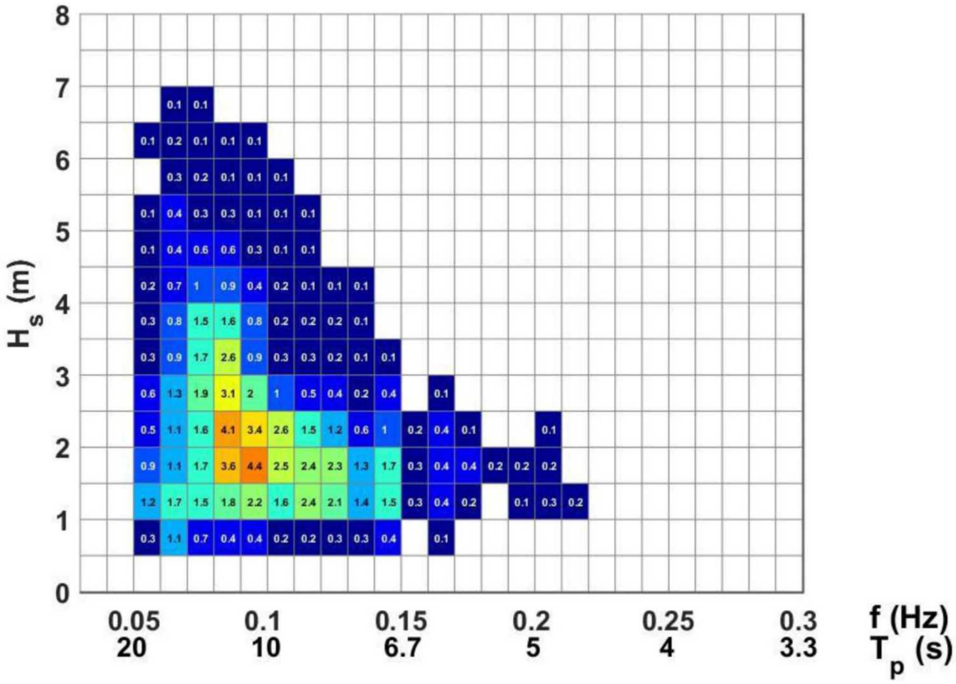

Figure 1—Joint probability distribution (JPD) of wave energy flux as a function of wave height and peak period (frequency also shown). JPD values are in units of percent occurrence and shaded from low (blue) to high (red) energy flux.

While excellent standards for wave resource assessments have been developed by the International Electrotechnical Commission (IEC 2012, 2015), wave resource assessment is still an active area of research. Due to the multivariate nature of the problem and the lack of long-term high-fidelity directional measurements at most sites, practical wave resource assessments are complex with multiple sources of uncertainty. Robertson (2017) has outlined excellent techniques for addressing many elements in a practical wave resource assessment; a basic wave energy transport approach is used in this study.

Annual Energy Production

While the wave resource is a fundamental metric for comparing specific sites, the AEP for a specific site and WEC device deployment provides the practical assessment for a project that allows for an investigation into pathways to decreasing the overall LCOE. To determine the AEP (kW/yr), the recoverable wave power is multiplied by the effectiveness of the WEC at capturing that power over a year. Multiple methods have been developed by organizations including the International Energy Agency's Ocean Energy Systems (OES 2015) and the International Electrotechnical Commission (IEC 2015) for determining AEP. The IEC and OES methods are the primary methods examined here.

The IEC methodology involves a comprehensive evaluation of a WEC's ability to produce energy from waves. To determine a WEC's effectiveness at capturing wave energy in varying sea states, a power matrix is constructed by applying a method of bins (IEC 2015). The WEC power matrix is the power produced over a range of sea states and developing a binned matrix of power produced as a function of wave height and period. Theoretical power matrices have been produced by Babarit et al. (2012) for eight different WECs that captured energy based on different operating principles (e.g., oscillating body, oscillating water column, overtopping). Figure 2 shows a theoretical power matrix produced by Babarit (2012) for a two-body heaving WEC. For the device shown, the maximum power for any combination of wave heights and periods for this WEC is 1,000 kW.

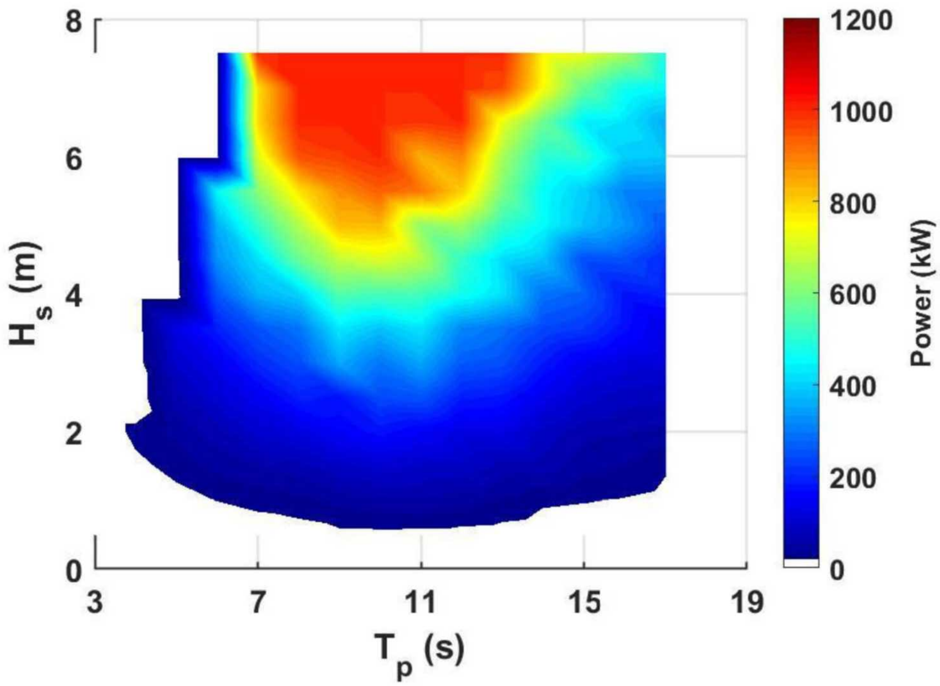

Figure 2—Example power matrix for a two-body heaving wave energy converter (Babarit et al. 2012). Power units in kW for a single WEC.

By using the wave power resource and the WEC characteristics, the AEP can be calculated. IEC (2015) suggests mean AEP be calculated as

$$AEP = T \sum_{n=1}^{N} L_i \, P_i \, f_i$$

where T is the time (1 year) multiplied by the WEC capture length (L), the wave power (P), and the frequency of occurrence of each power bin i where N is the total number of bins in the JPD or wave power and capture lengths. Capture length, essentially another method for expressing the WEC power matrix, is the net electrical power captured divided by wave energy flux (L=P/J) for a particular wave height and period in the JPD. The IEC standards recommend that a minimum of 10 years of data be used for the evaluation. While this methodology is the present industry standard, other methods prove useful to the goals of the present AEP evaluation.

OES (2015) uses a broader definition of AEP that makes larger assumptions about a site and device. Though these larger assumptions introduce uncertainties that are beyond the scope of this study, for the purposes considered here, the OES method is adequate for the evaluation. The OES AEP is calculated as

$$AEP = PC \cdot CF \cdot AF \cdot T$$

where PC is project capacity, AF is the availability factor, CF is device capacity factor, and T is the time (1 year). The project capacity is the WEC's rated capacities (units of power, e.g., kW) multiplied by the number of devices. The capacity factor is the actual energy produced divided by the power rating. A device's availability factor is defined as the "[a]vailability of a marine energy conversion system to be in a state to perform a necessary function under given conditions at a given instant of time over a given duration" (OES 2015). Essentially, the AEP is the product of the WEC's power matrix, the JPD for the WEC deployment site, the percentage of time the WEC is operational (i.e., not shut down for maintenance or protection), and the total number of devices within the WEC array.

Wave Energy Resources

Four different U.S. Pacific coast locations were used in this study to determine the power production of WEC deployments in this study: Umpqua, Oregon; Monterey and Point Conception, California; and Mokapu, Hawaii (Figure 3). These locations were chosen because long-term wave records are available at these sites and, except for Monterey, California. Extensive wave analysis and WEC array modeling was leveraged for the Monterey site, allowing it to be readily incorporated into this study (Chang et al. 2014, 2016). As recommended in the IEC standards, wave records spanning a period of 10 years were obtained from the National Oceanic and Atmospheric Administration National Data Buoy Center (NOAA NDBC).

Figure 3—Four locations used for the determination of AEP from existing wave data.

The JPDs of wave energy flux were calculated directly from the measured wave records at each site to provide an indicator of site characteristics (Figure 4). As expected, the mainland west coast locations are similar due to their configuration in the Pacific basin. The maximum wave energy occurrence is approximately 30 kW/m. The Umpqua site has the highest wave energy flux and the energy occurs in the narrowest directional band. The wave climate for Mokapu has a much larger directional spread than the mainland sites. At Mokapu, the maximum wave energy flux has most frequent occurrence of energy flux is from northeast trade swell directions (Figure 4D).

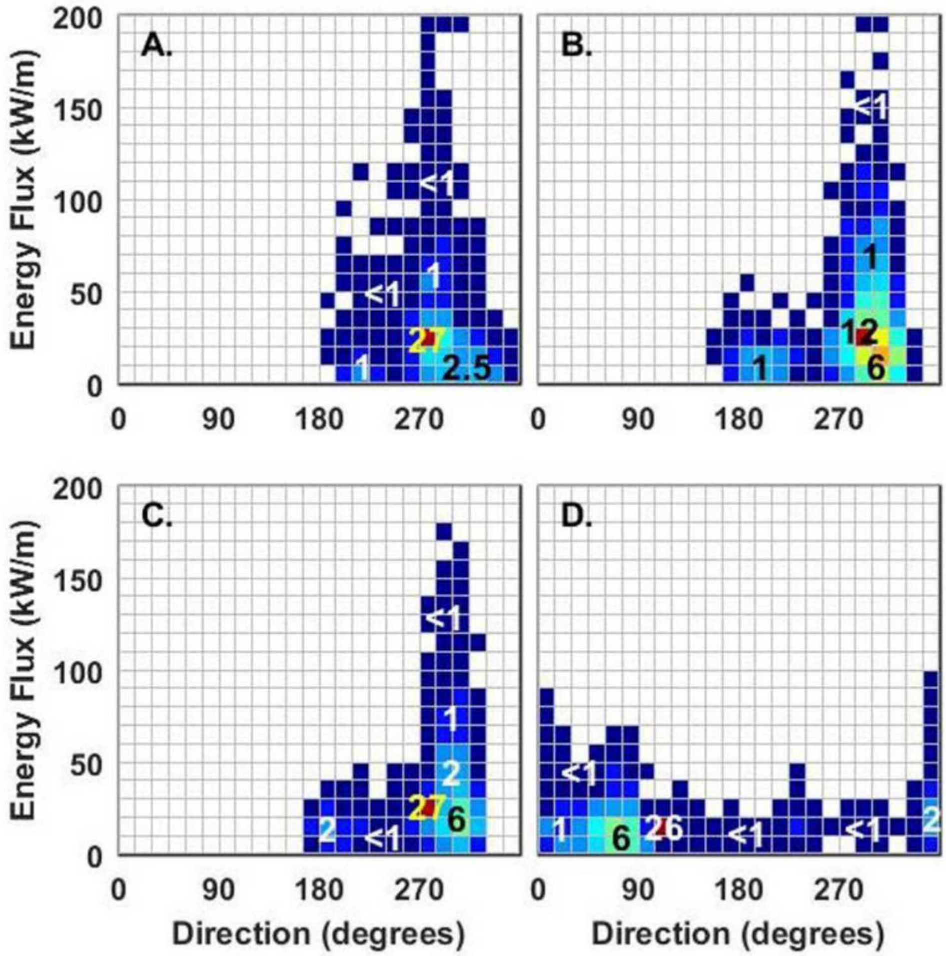

Figure 4—JPD of energy flux as a function of direction for Umpqua, OR (A); Monterey, CA (B); Point Conception, CA (C); and Mokapu, HI (D).

Wave Energy Conversion Devices

To determine the power produced at the four sites, power matrices for specific WEC devices were multiplied by the JPD of the energy flux at each site. For this investigation, six WEC devices were used: floating heave-buoy array (F-HBA), floating two-body heaving converter (F-2HB), floating oscillating water column (F-OWC), bottom-referenced heaving buoy (Bref-HB), bottom-referenced submerged heaving buoy (Bref-SHB), and floating three-body oscillating flap device (F-3OF). Power matrices for six WECs were numerically modeled by Babarit et al. (2012) (Figure 5). By multiply the wave resource JPD by the power matrix for each site and device, the total energy for each device at each location was calculated. The AEP was calculated as the yearly average of total energy production from the measured wave record. It is important to note that the WECs were not analyzed for their suitability for deployment along the U.S. Pacific coast in particular, but are used here to represent a variable range of power generation characteristics.

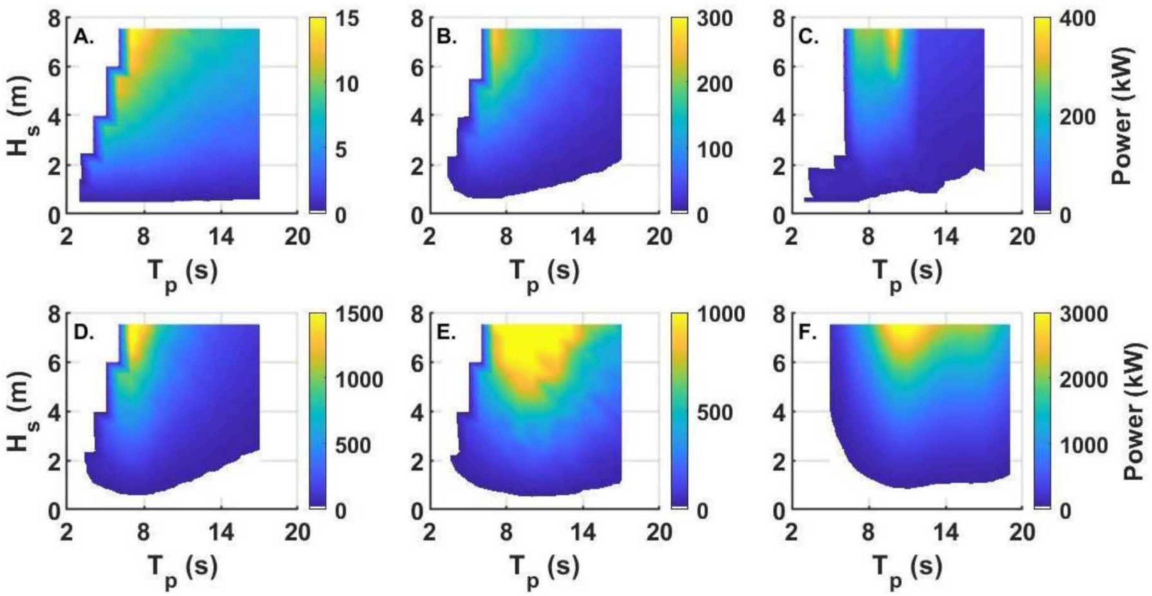

Figure 5—Power matrices for six WECs numerically modeled by Babarit et al. (2012). A. Bref-HB, B. Bref-SHB, C. F-HBA, D. F-3OF, E. F2HB, F. F-OWC.

While one aspect of the availability factor (AF) is dependent on an assumption of downtime due to WEC maintenance, the other aspect is dependent on the time a WEC is shut down for protection during storms, which is site specific. The continuous wave measurements made over 10 years at each site enabled the estimation of an average AF for each site, following

$$AF = 1 - [(T_{shutdown} + T_{servicing})/T_{total}]$$

where $T_{shutdown} + T_{servicing}$ is the time over the course of 1 year that the device is not operating due to protective shutdown and routine maintenance and T_{total} is 1 year. It is assumed here that protective shutdown occurs when wathe wave height exceeds 4.5 meters (m) and maintenance shutdown occurs 1 week per year (Chang et al. 2018). Because AEP and AF are computed, the CF is calculated by dividing the AEP by the power rating for each WEC.

Array Configurations

In addition to the number of WECs in an array, the shape, spacing, and placement of the array can have a substantial effect on the AEP of a WEC project. A basic evaluation of WEC array configurations was performed using a version of Simulating Waves Nearshore developed by Sandia National Laboratories (SNL-SWAN) numerical model (Ruehl et al. 2014, 2015). SNL-SWAN is a modified version of the industry standard wave modeling tool, SWAN (Booij et al. 1999), which was developed to incorporate WEC effects on wave energy. SNL-SWAN incorporates WEC-specific wave power extraction into the model. Various SNL-SWAN options allow for specification of WEC power matrices in the model. While an extensive evaluation of array configurations and performance is beyond the scope of this study, a few basic array configurations are included to demonstrate the potential sensitivity of AEP to array configuration.

While four sites are investigated in this study for overall AEP evaluation, higher fidelity hydrodynamic and wave modeling with simulated WEC arrays have been conducted for the Monterey Bay, California, site. Therefore, similar to previous work conducted in Chang et al. (2014, 2016), high resolution SNL-SWAN models were used to simulate the offshore Monterey Bay and nearshore Santa Cruz waters in California to investigate the effects of array configuration on AEP. Three different arrays of 50 F-2HB devices were simulated in the Monterey Bay SNL-SWAN model including a diamond-shaped array, five staggered cluster arrays of 10 devices, and a simple line array (Figure 6). The WEC array was simulated with spacing of three times the water depth for each device. These arrays are not chosen to represent realistic or feasible deployments, but rather only to offer variable configurations. The array evaluations were performed using the Babarit et al. (2012) power matrix for the F-2HB device. For the basic evaluation here, only single sea states were used to directly compare the array performance. The modeled boundary conditions included the mean wave conditions of all waves coming from 180° for the Monterey Bay NDBC station. The maximum power produced for the three WEC array configurations was compared to evaluate energy production due to array changes.

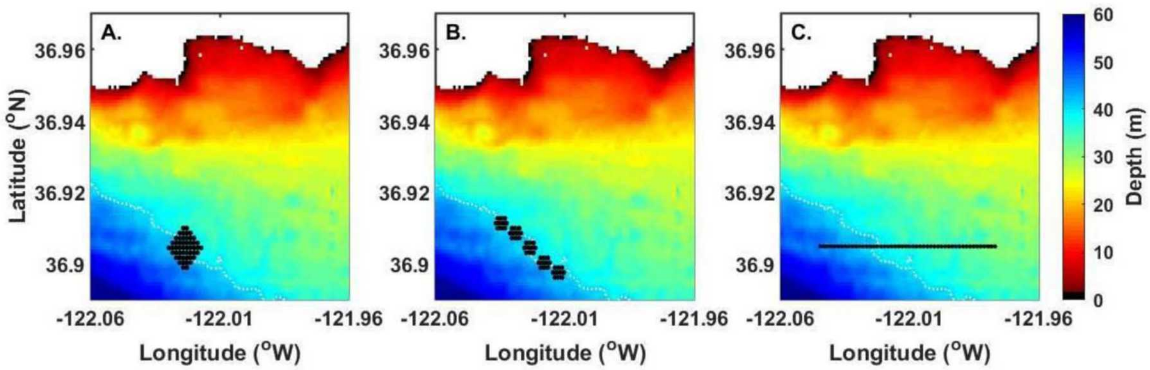

Figure 6—WEC array configurations (black dots) evaluated in Monterey Bay, CA.

Results and Discussion

Annual Energy Production

The power and energy production per year were computed for each WEC and location for the available NOAA wave record at each of the four sites as outlined in the previous section. The power produced and energy production vary among the simulated WEC device's power ratings and the sites (Figure 7). The F-OWC WEC has the highest power production and average energy production across all of the sites. This is expected because the F-OWC has the greatest power production capacity of any of the modeled WECs (Figure 5). Interestingly, while the the F-3OF device has a higher peak power than the F-2HB device, the peak power is produced only over a narrow frequency band outside the peak energy at all locations. Therefore, the F2HB WEC outperforms the F-3OF at all of the locations evaluated (Figure 7).

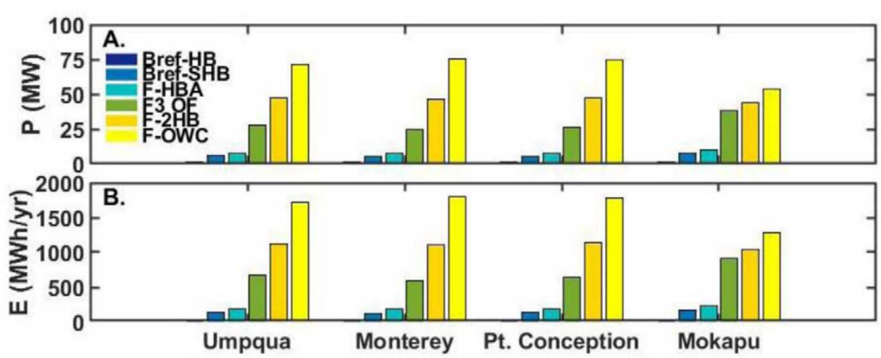

Figure 7—Power produced and average energy production per year for the six WEC devices at the four locations investigated.

The F-HBA, Bref-HB, Bref-SHB, and F3-OF all have peak power production in wave periods of less than 10 seconds (s) and perform better at Mokapu. These four theoretical WECs absorb up to 50 percent more power at Mokapu. However, for the WECs with peak wave periods around 10 s, the F-OWC and F-2HB, the Oregon and California sites produce the best power production (Figure 7). Further evaluation of these results can provide insights for specific-site assessments when fed into economic models such as Teillant et al. (2012).

Availability and Capacity Factors

Variations in power production are directly dependent on the availability of a WEC to produce energy during a deployment. Of the four sites evaluated, the availability factor is lowest for Umpqua, with 30 shutdown days per year resulting in an AF of 90 percent. The Point Conception and Monterey sites have approximately 10 days of shutdown resulting in AFs of 95 and 96 percent, respectively. The Mokapu wave conditions generally have lower wave heights resulting in less than 1 protective shutdown day per year (an AF of >98 percent). Data from WEC studies worldwide show AFs of 95–98 percent (OES 2015) providing a potential target for future WEC projects.

The capacity factor for the WECs at each site can be computed from the energy production and availability factor. For the conditions evaluated, the CFs have a wide variability between 10 and 30 percent (Figure 8). Interestingly, the capacity of the Bref-SHBA and F-HBA increase in Mokapu, while the values decrease for the F-OWC and F-2HB mirroring the energy production at each site.

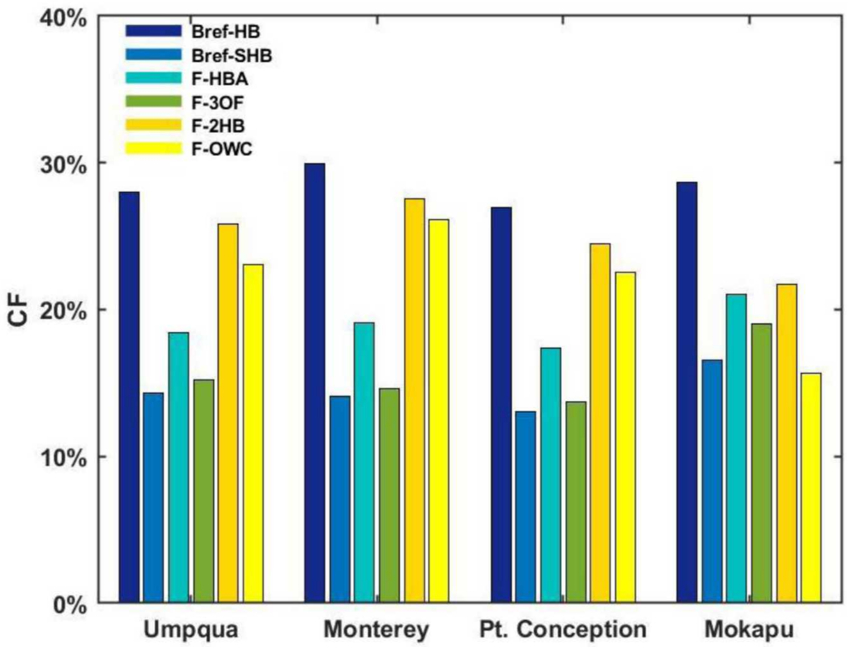

Figure 8—Calculated capacity factors for the evaluated WECs at the four sites.

Only the highest capacity factors here (Bref-HB) are consistent with the CFs of 30 ± 5 percent reported by others (e.g., Sandia 2014; Jenne et al. 2015; OES 2015; Salvatore 2013; Yu et al. 2015) suggesting that there is still further work to be done in the community to better characterize WEC capacity factors. While there is substantial variation in the values, the results illustrate the usefulness of the capacity factor as a metric in combined WEC and site evaluations.

Array Configurations

The WEC array simulations showed that the overall energy production can increase by more than 20 percent with different array shapes (Figure 6). The greatest differences in power absorption are determined between the diamond and line arrays. It is important to note, that these configurations are not feasible in practice, and are only used for illustrative purposes here. During average wave conditions at the Monterey Bay site (H_s = 1.6 m), five clusters of 10 WECs absorb approximately 10 percent more power than a diamond array (Chang et al. 2018). Notably, only 3 percent more power is absorbed for a line array than for a diamond array.

Barring considerations such as construction efficiencies, cabling, and maintenance, array configuration can have a substantial effect on the AEP and must be considered in the final site design.

WEC Controls

Both active and passive control strategies are understood to increase power absorption characteristics of a WEC (Babarit 2004; Hals et al. 2011). In simulations, passive control methods have been modeled to increase the power production of WECs by 100 to 200 percent (Belmont 2012). Further active control strategies can theoretically increase WECpower production by more than 300 percent (Hals et al. 2011; Li et al. 2012). More recently, Wilson et al. (2016) have used robust analyses and reported increases in AEP from 46 to 197 percent. While the effects of controls cannot be directly simulated here given the detail of the WEC-specific information necessary, it is important to consider that substantial AEP increases are possible with implementation of control strategies.

Conclusions

The assessment of a wave energy conversion project's AEP by a developer is fundamental in determining if the project is feasible for providing power to the electrical grid. Many factors are involved in conducting the overall project assessment, including a full cost–benefit analysis, utility costing, and myriad other factors, but the wave resource is foundational in the project assessment (Robertson 2017; Sandia 2014; Telliant et al. 2012). The goal of a site resource assessment is to determine the AEP for a specific site and WEC deployment strategy at that site. This study illustrates basic evaluations of the energy produced by a WEC or WEC array at four different sites to understand the factors affecting AEP (Figure 9). The pathways evaluated included site selection, WEC characteristics, and WEC array configurations.

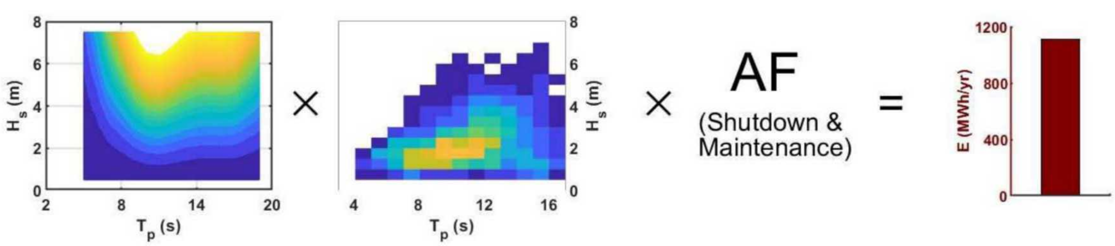

Figure 9—Graphical representation of factors governing the calculation of AEP and LCOE for a site (adapted from Chang et al. 2018).

The basic resource assessments of the four Pacific sites illustrate that while a site might have the highest energy of sites evaluated (Umpqua), the energy may be in a bandwidth not readily captured by some WEC designs and might result in much larger protective shutdown periods. Conversely, while lower energy sites (Mokapu) may have a broader bandwidth of energy and more accessible wave conditions, the overall energy production is significantly lower. The variation of characteristics beyond simple energy flux, such as directionality, variations of heights and periods, and temporal characteristics, play as important a role in project design as the available resource.

The AF and CF values for the sites were also evaluated to investigate the effect of WEC characteristics on AEP. Data from other WEC studies worldwide show AFs of 95 to 98 percent (OES 2015), providing a potential target for WEC projects. As seen in the analysis here, the nature of the resource can result in AFs varying from 90 (Umpqua) to more than 98 percent (Mokapu). When considering OPEX in addition to the resulting AEP for a site, the ~8 percent variation in the AF plays an important role in project evaluation. Likewise, CF values varied from approximately 15 to 30 percent at a single site depending on the type of WEC deployed. While a developer always has a goal of maximizing CF for a site to increase AEP, the CF can be important for a cost–benefit analysis. Also, while the CF value for a particular WEC may be low at one site, it may significantly increase at another site. Though there is substantial variation in CF values, the results illustrate the value of CF as an important metric in combined WEC and site evaluations.

Other WEC project design considerations providing pathways to increased AEP are control strategies and array configurations. In addition to the growing body of theoretical work on the topic, Wilson et al. (2016) have recently used robust analyses and reported increases of AEP from 46 to 197 percent depending on the control strategy implemented. The potential for significant increases in AEP from controls bring the implementation of WEC-specific control strategies to the forefront of required project elements. Array configurations modeled for a single site (Monterey Bay) offer a simple evaluation of three arrays. Even screening level analyses here indicate that significant (~20 percent) gains can be made with changes in array configurations.

The success of commercial-scale WEC deployments will require accurate assessment of wave resources, continued reduction of CAPEX and OPEX estimates, WEC design and deployment improvements, and development and implementation of control strategies to increase array energy production. The careful consideration of the factors outlined here will result in optimized AEP for projects. Ongoing work in these areas will continue to support the growth of the nascent wave energy industry so that it has a permanent place in the global energy inventory.

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References

Babarit, A., J. Hals, M.J. Muliawan, A. Kurniawan, T. Moan, and J. Krokstad. 2012. Numerical benchmarking study of a selection of wave energy converters. *Renew. Energy* **41**(2012):44–63.

Belmont, M.R. 2012. *Increases in the Average Power Output of Wave Energy Converters Using Quiescent Period Predictive Control*, Elsevier Ltd.

Booij, N., R.C. Ris, and L.H. Holthuijsen. 1999. A third-generation wave model for coastal regions. Part I: Model description and validation. *J. Geophys. Res*. **104**:7649–7666.

Chang, G., J. Magalen, C. Jones, J. Roberts. 2014. Investigation of Wave Energy Converter Effects on Wave Fields: a Modeling Sensitivity Study in Monterey Bay, CA. *Sandia National Laboratories Report*, SAND2014.

Chang, G., K. Ruehl, C.A. Jones, J. Roberts, C. Chartrand. 2016. Numerical modeling of the effects of wave energy converter characteristics on nearshore wave conditions. *Renew. Energy* **89**(2016):636e648.

Chang, G., C.A. Jones, J.D. Roberts, and V.S. Neary. 2018. A comprehensive evaluation of factors affecting the levelized cost of wave energy conversion projects. *Renew. Energy* **127**(2018):344–354.

EPRI. 2011. *Mapping and Assessment of the United States Ocean Wave Energy Resource. 2011 Technical Report*. Electric Power Research Institute.

Hals, J., J. Falnes, and T. Moan. 2011. A comparison of selected strategies for adaptive control of wave energy converters. *J. Offshore Mech. Arctic Engr*. **133**(3). doi.org/10.1115/1.4002735.

IEC. 2012. *Technical specification. Marine energy—Wave, tidal and other water current converters. Part 100: Electricity producing wave energy converters—Power performance assessment. IEC/TS 62600-100. Edition 1.0 2012-08*. International Electrotechnical Commission.

IEC. 2015. *Technical specification. Marine energy—Wave, tidal and other water current converters. Part 101: Wave energy resource assessment and characterization. IEC TS 62600-101. Edition 1.0 2015-06*. International Electrotechnical Commission.

Jenne, D.S., Y.-H. Yu, and V. Neary. 2015. Levelized cost of energy analysis of marine and hydrokinetic reference models. In: Proceedings of the 3rd Marine Energy Technology Symposium, Washington, DC, NREL/CP-5000e64013.

Li, G., G. Weiss, M. Mueller, S. Townley, and M.R. Belmont. 2012. Wave energy converter control by wave prediction and dynamic programming. *Renew. Energy* **48**(2012):392–403.

OES. 2015. *International Levelised Cost of Energy for Ocean Energy Technologies*, 48 pp. Ocean Energy Systems. May.

OES. 2017. Annual Report. An Overview of Ocean Energy Activities in 2017. Ocean Energy Systems.

Robertson, B. 2017. Wave energy assessments: Quantifying the resource and understanding the uncertainty. *Marine Renewable Energy* doi: 10.1007/978-3-319-53536-4–1

Ruehl, K., C. Chartrand, and A. Porter. 2014. *SNL-SWAN Manual, SAND Report*, Sandia National Laboratories, Albuquerque, NM.

Ruehl, K., A. Porter, C. Chartrand, H. Smith, G. Chang, and J. Roberts. 2015. Development, Verification and Application of the SNL-SWAN Open Source Wave Farm Code. In: Proceedings of the 11th European Wave and Tidal Energy Conference, Nantes, France.

Salvatore, J.S. 2013. World Energy Perspective: Cost of Energy Technologies. G. Turner, H. Boyle, E. Nekhaev, A. Clerici, and S. Ulreich (Eds.). World Energy Council Regency House, London, UK.

Sandia. 2014. *Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies. SAND2014-9040*. Sandia National Laboratories, Water Power Technologies Department, Albuquerque, NM.

Teillant, B., R. Costello, J. Weber, and J. Ringwood. 2012. Productivity and economic assessment of wave energy projects through operational simulations. *Renew. Energy* **48**(2012):220–230.

Wilson, D., G. Bacelli, R.G. Coe, D.L. Bull, O. Abdelkhalik, U.A. Korde, and R.D. Robinett III. 2016. A comparison of WEC control strategies, *Sandia National Laboratories Report, SAND2016-4293*.

Yu, Y.-H., D.S. Jenne, R. Thresher, A. Copping, S. Geerlofs, and L.A. Hanna. 2015. Reference Model 5 (RM5): Oscillating Surge Wave Energy Converter. *National Renewable Energy Laboratory Technical Report NREL/TP-5000-62861*, Golden, CO.