www.oregonwave.org

Wave Energy Utility Integration

Advanced Resource Characterization and Integration Costs and Issues

Prepared by
Pacific Energy Ventures (J. Klure), Ecofys (K. Dragoon), Jeff King and Gordon Reikard
On behalf of the Oregon Wave Energy Trust

December 31, 2013

This work was funded by the Oregon Wave Energy Trust (OWET). OWET was funded in part with Oregon State Lottery Funds administered by the Oregon Business Development Department. It is one of six Oregon Innovation Council initiatives supporting job creation and long-term economic growth.

Oregon Wave Energy Trust (OWET) is a nonprofit public-private partnership funded by the Oregon Innovation Council. Its mission is to support the responsible development of wave energy in Oregon. OWET emphasizes an inclusive, collaborative model to ensure that Oregon maintains its competitive advantage and maximizes the economic development and environmental potential of this emerging industry. Our work includes stakeholder outreach and education, policy development, environmental assessment, applied research and market development.

Table of Contents

Acknowledgements

The authors would like to express their gratitude to the Oregon Wave Energy Trust for making this study possible. We would also like to thank the stakeholder advisory group members who helped define this project and help ensure its usefulness to the broader energy community.

Thanks also are due to Bart McManus and the Bonneville Power Administration (BPA) for supplying data from the BPA system, without which this project would have been much more difficult or less precise — likely, both.

Special gratitude to Dr. Tuba Özkan-Haller, Dr. Ted Brekken, and Oregon State University for their support of modeling, data and expertise that also made this project possible.

Disclaimer

The specific wave energy technologies referenced in this report were used only to help better understand how electric utilities might forecast the amount of electricity produced from potential wave energy projects and evaluate the costs and issues to integrate the potential power into the electric grid. The devices noted herein are used for illustrative purposed only, and are not representative of any official power output for any individual technology. No individual company or technology developer provided specific performance details for this analysis, or was consulted for this report. Public sources of information were used to help populate the forecasting and integration models developed under this project. All energy output calculations and project scenarios are hypothetical in nature.

I. Project Background and Overview

Pacific Energy Ventures has partnered with utility industry and variable energy resource characterization experts, Ken Dragoon (Ecofys), Jeff King and Gordon Reikard to provide the Oregon Wave Energy Trust (OWET) a comprehensive analysis aimed at further validating wave energy as an economical and viable part of the Northwest's energy portfolio. This project relied on advanced analytical and evaluation techniques to 1) develop an improved understanding of the time-dependent power of waves along the Northwest coast, 2) determine hypothetical electrical output of representative wave energy converter designs deployed at prospective development sites along the Oregon coast, and 3) evaluate the magnitude of balancing capacity reserves needed to integrate wave-generated electricity into the Northwest electrical grid.

Purpose and Objectives

The overall purpose of this project was to provide an analysis of wave energy resources so as to inform utilities and balancing authorities about potential integration issues and costs, overall resource characterization, and methods for managing them. Specific objectives include:

Objective 1 – Advanced Resource Assessment:

- Provide an analysis of the hourly, daily, and seasonal wave resource and variability of energy potential.
- Characterize the predictability of wave energy and develop methods for near-term (sub-hourly to days) forecasting of the output of wave energy projects using both large scale physics-based models and statistical models such as persistence, regression and neural networks.

Objective 2 – Quantify the Integration Costs

- Develop an estimate of relative integration costs for wave energy based on Bonneville Power Administration's (BPA) current integration cost methodology.
- Incorporate utility feedback on all elements of the project by convening the Utility Advisory Group (UAG) to review and analyze data and work products.

The rapid and large-scale development of wind generation in the Northwest has necessitated changes in the utilities' load balancing procedures to accommodate wind's greater variability. Although it is generally agreed that wave energy is more predictable than wind, it will likely face similar integration challenges as the industry matures. This project attempts to develop tools to help quantify the cost and value of introducing wave energy into the Northwest's energy mix.

Key Findings

This study provides evidence that wave energy integration is manageable, and that wave energy has the potential to contribute a great deal of electricity to the power grid. It shows areas where additional study is warranted (See Section V. Conclusions and Recommendations) and the potential for substantially more accurate resource forecasts by incorporating data from distant observation sites. The study broke new ground in using data from buoy observations, and the use of advanced computational models to develop sub-hourly data from hourly observations. Finally, the embedded analysis emphasizes the need for improvements in wave forecasting models to better capture energy aspects of wave behavior.

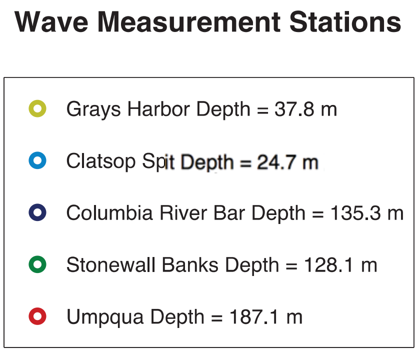
Report Organization

The report that follows consists of four sections: Section II is a characterization of the wave energy resource of the Northwest coast and a review of wave energy converter (WEC) designs that might be used to generate electricity from this resource and a discussion of how the energy output of a WEC is calculated from wave data. Section III is an evaluation of alternative approaches to forecasting the wave energy flux, with recommendations. Section IV is an evaluation of balancing reserve requirements needed to integrate wave-generated electricity into the Northwest electrical system with a cost example. Section V is a summary of conclusions and recommendations stemming from this study. Two appendices conclude the report: First, a description of the stakeholder engagement process accompanying the study and second, a glossary and description of acronyms.

II. Resource Characterization

Because wave farms have yet to be developed in the Northwest, the study relies primarily on simulations based on historical time series data of wave height (meters) and period (seconds). Wave height and period data are used to estimate the wave energy flux, the potential electric energy that can be generated using specific types of wave energy converters (WECs), and simulated time series of wave energy production at specific locations. Ten-minute data is ideal to fully evaluate integration costs, but as described below, the available data is only in hourly or 30-minute intervals.

Wave height and period data were obtained from records of five data buoys off the Northwest coast, maintained by the National Data Buoy Center, a department of the National Oceanographic and Atmospheric Administration (www.ndbc.noaa.gov). The selected data buoy stations are Clatsop Spit, Grays Harbor, Columbia River Bar, Stonewall Banks, and Umpqua (Figure 1). As is often the case with buoy data, missing values are an issue. The five stations that were selected have reasonably complete records spanning several years.



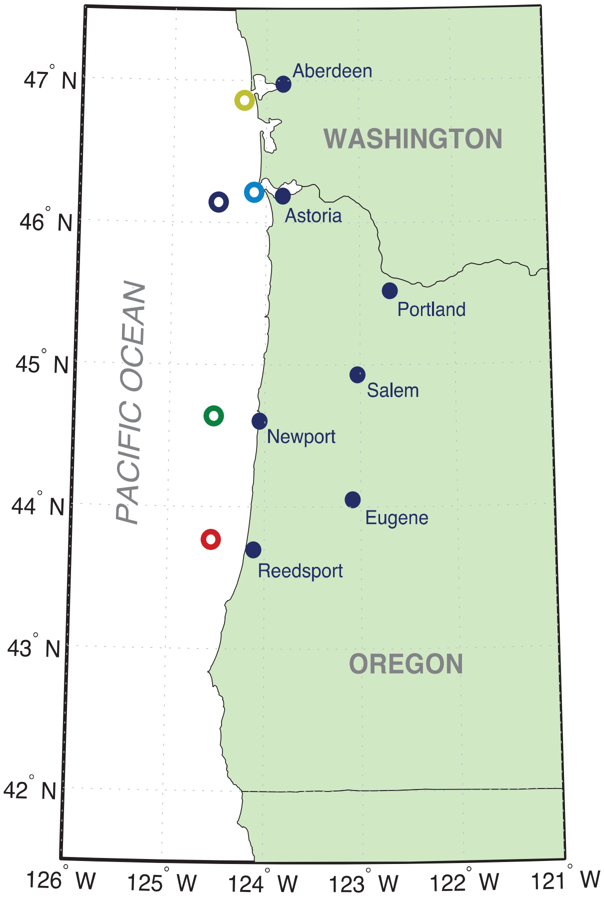


Figure 1: National Data Buoy Center data buoy stations used as sources of wave height and period historical time series data for this study

Three stations (Columbia River Bar, Stonewall and Umpqua) are in deep water, while two (Clatsop Spit and Grays Harbor) are in shallower coastal locations, more typical of prospective wave energy installations. Though there are several monitoring stations along the coast at locations including Tillamook Bay and Newport, most of these are missing the necessary data on wave height and period. The only shallow water sites that have reasonably complete data are Clatsop Spit and Grays Harbor. Though located in Washington State, Grays Harbor shows similar properties to Clatsop Spit, and provides a reasonably good proxy measure of the Oregon coast wave conditions.

Basic information on the five data buoy stations used for this study is provided in Table 1.

Station Number	Name	Latitude	Longitude	Depth	Data Resolution
NDBC 46211	Grays Harbor	45.87 N	124.24 W	37.8 m	30 minutes
NDBC 46243	Clatsop Spit	46.215 N	124.128 W	24.7 m	30 minutes
NDBC 46029	Columbia River Bar	46.144 N	124.510 W	135.3 m	Hourly
NDBC 46050	Stonewall	44.639 N	124.534 W	128.1 m	Hourly
NDBC 46229	Umpqua	43.769 N	124.551 W	187.1 m	30 minutes

Table 1: Information regarding National Data Buoy Center stations used for this study

Hourly data was downloaded for the three-year period January 1, 2009 through December 31, 2011. The Umpqua and Clatsop Spit data, which are available at 30-minute intervals, were converted to hourly averages to make these data sets comparable to the others. The monthly data was downloaded as far back as available (i.e., the hourly values were downloaded, and consolidated up to monthly averages).

In some of the longer-term data sets, entire months and sometimes several months are missing. Missing hourly values were created using linear interpolation using the same month from previous or subsequent years.

The hourly and monthly time series of wave height and period used for this study are posted at www.oregonwave.org. The hourly databases are designated as follows:

- OWET_Clatsop1
- OWET_GraysHarbor1.xls
- OWET_Umpqua1.xls
- OWET_Columbia1.xls
- OWET_Stonewall1.xls

At the monthly resolution, a second set of databases was developed and used for analysis. These are: OWET_Clatsop_Monthly2.xls, etc. In these databases, the interpolated monthly series were used. The power converters did not exist during earlier years, so the calculations indicate what the power output would have been if the devices had been available. This can be useful in assessing the long-term power output that can be expected from wave farms. Two columns appear in the monthly databases, one for the original download, and a second for interpolated data sets.

The data definitions for both the hourly and monthly databases are as follows:

HS = the significant wave height, in meters.
TP = the peak wave period.
TM = the mean wave period, in seconds.
State (Hourly only)= A (1,0) binary variable set equal to 1 when the data is interpolated, and 0 for the actual values.

Theoretical Wave Energy Potential

The wave energy flux (energy potential) is proportional to the square of the wave height and to the wave period (see sidebar for further discussion), and is defined as energy per unit length of wave crest. Two values of the flux were calculated, one based on the peak wave period and a second on the mean wave period. The flux calculated on the mean wave period is smaller, but more representative of the extractable energy. The two fluxes are defined in the databases as follows:

Flux 1 = Flux calculated using the peak wave period.
Flux 2 = Flux calculated using the mean wave period.

The wave energy potential available to a single line of WECs is therefore the unit flux times the length of installation. The average flux for the deep water sites is 30.08 kW/m. The length of the Oregon coastline is 580 kilometers. Therefore, in the deep water sites, the potential is 17.46 GW, i.e., 30.08 kW/m x 580,000 m. The same calculation can be run for the shallow coastal sites. The average flux for Clatsop Spit is 24.4. This would imply a value of 14.18 GW for shallow coastal sites. At Grays Harbor, the mean value of the flux is 23.69 kW/m, yielding 13.74 GW of potential power. The average of the two sites is 13.96 GW.

Calculating Wave Energy

The standard calculation for wave energy is the flux, denoted by E_{Ft}. Let *g* denote the acceleration caused by gravity (9.8086 m/s/s). Let *ρ* denote the density of seawater (1025 kg/m^3). Let H_S denote the significant wave height, in meters. Let T_{Mt} denote the mean wave period, in seconds. The flux, in kilowatts per meter (kW/m) of crest length, is given by:

$$E_{Ft} = [(g^2\rho / 64\pi)\, H_{St}^{\;2}\, T_{Mt}\ ] / 1{,}000 \approx 0.4907\, (H_{St}^{\;2}\, T_{Mt})$$

In other words, the flux is a function of the squared wave height and the wave period. Note that the flux can also be calculated using the peak wave period, T_{Pt}, although the implications of the formula remain the same.

For more on calculating wave energy, see Holthuijsen (2007)[1].

These calculations are based on two lines of converters, one in shallow water, the other in deep water, both stretching from the northern to the southern border of the state. The 2011 EPRI report *Mapping and Assessment of the United States Wave Energy Resource* gives figures that are several orders of magnitude higher, on the order of 179 TW in deep water and 140 TW in shallow water. The smaller figures are probably more realistic, since only a fraction of the energy is likely to be extracted.

In the monthly databases, several findings should be noted. The first finding being that the flux is lower in the shallow coastal regions than at greater depths. Looking at the monthly data, the power fluctuations align with seasonal variation. While there is some difference year-to-year, it is not clear whether this is related to any climatic phenomena, for instance the El Nino cycle. The troughs of the seasonal cycles (July-August) often show very similar values.

One important caveat is implied in interpreting these data sets: Given the number of missing values, the degree of interpolation required even to create long monthly histories was substantial. The long histories are useful primarily in that they establish the average monthly values for the flux and the potential power.

---

[1] Holthuijsen, L.H., 2007. Waves in Oceanic and Coastal Waters. Cambridge University press.

Commercial Project Development Sites

The State of Oregon has designated a series of locations along the Oregon Coast that are most suitable for commercial development. These locations are the result of a multiyear process lead by the State to revise the Territorial Sea Plan (TSP) to accommodate for future wave energy projects.

Four sites have been identified and designated as "Renewable Energy Facility Site Suitability Areas (REFSSA)," which are areas where ocean renewable energy companies will be encouraged to develop first. A fifth location in Newport, is being developed by Oregon State University as the nation's first grid-connected test facility, the Pacific Marine Energy Center South Energy Test Site (PMEC-SETS). Two of the REFSSA sites are ideal for near shore technologies, while the other two are preferable for deep-water technology. All of the sites were selected based on several factors, including access to electrical grid connections, access to deep-water ports and service ports, ocean bottom type, bathymetry, and avoidance of conflict with ocean resources and existing users of those resources. The outcome of this exercise emphasizes the simple fact that there are limited areas suitable for development due to competing uses of the sea-space and environmental considerations.

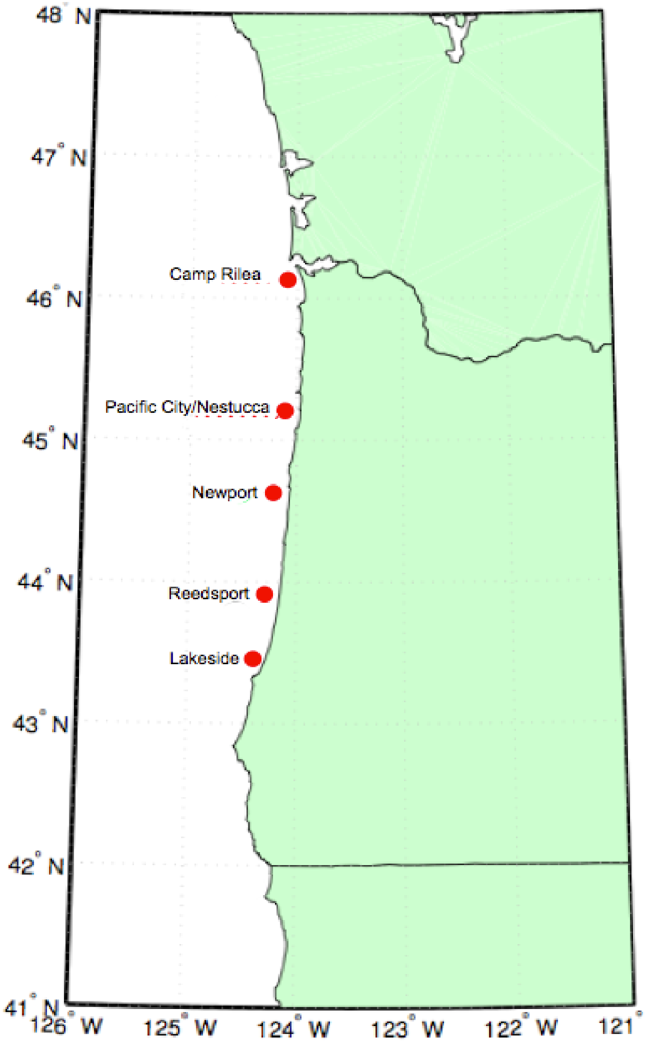


Figure 2: Renewable Feasibility Site Areas Identified by State of Oregon

Wave Energy Converters

Wave energy conversion devices convert the kinetic and potential energy comprising the wave energy flux to electric power. WECs are at a relatively early stage of development. Many conceptual designs have been advanced over the past several decades, but only few have been deployed commercially, and the most cost-effective designs for given site conditions remain to be established. For this reason, time series of the energy output of six WEC concepts were simulated. Two concepts, the Pelamis and the Wavestar, are approaching early commercial deployment. Four other WEC's analyzed for this study are at earlier stages of development.

The Pelamis P2 Device

The Pelamis P2 is the most mature of the six WEC concepts analyzed in this study. Test deployment of first generation Pelamis commenced in 2004. The second generation machine, the Pelamis P2, is undergoing testing at the European Marine Energy Centre in the Orkney Islands. Early commercial-scale wave farms using the Pelamis P2 are under development in the Shetland Islands, Outer Hebrides and

Sutherland Coast of Scotland. The Pelamis is designed as an offshore wave energy converter, for depths greater than 50 meters. The machine consists of a series of semi-submerged cylindrical sections linked by hinged joints. As waves pass along the length of the machine, the sections move relative to one another. The wave-induced motion causes hydraulic cylinders to pump high pressure oil through hydraulic motors. These in turn drive electrical generators. The resulting electricity is transmitted through an umbilical cable to a junction on the sea bed. Several devices can be connected and linked to shore through a single seabed cable.

The Pelamis is an attenuating wave energy converter designed with survivability at the fore. The machine responds to the curvature of the waves rather than the wave height. As waves can only reach a certain curvature before naturally breaking this limits the range of motion through which the machine must move but maintains large motion at the joints in small waves.

The Wavestar Device

Only one of the six WEC concepts examined, the Wavestar device (www.wavestarenergy.com) is designed for shallow sites. The Wavestar is under development in Norway, and a half-scale demonstration project is currently in operation. The Wavestar machine draws energy from wave power with floats that rise and fall with the up and down motion of waves. The floats are attached by arms to a platform that stands on legs secured to the sea floor. The motion of the floats is transferred via hydraulics into the rotation of a generator, producing electricity. Waves run the length of the machine, lifting a series of floats in turn. Powering the motor and generator in this way enables continuous energy production and a smooth output. For values of the wave height about 3 meters, the rated capacity of each Wavestar converter was assumed to be 600 kW.

Four Additional Devices Under Development

Conversion matrices for several other types of deep water devices were calculated in Babarit et al., (2012)[2]. These technologies are in the early development stage. They include:

- *Floating two-body heaving converter:* This device is a detached buoy with an axial-symmetric point absorber. The internal mechanism uses a torus, which slides along a vertical float. The power is generated by the relative motion of the two bodies. This device is currently under development in Ireland. The rated capacity of each device assumed in the simulations is 1000 kW.
- *Floating heaving buoy array:* This is composed of several heaving buoys connected to a fixed submerged structure. The buoys are connected to the fixed structure via a hydraulic system, which powers an electrical generator. This device is currently under development in Norway. In the conversion matrix, the number of buoys was limited to ten. The rated capacity assumed in the simulations is 3619 kW per device.
- *Floating three-body oscillating flap device:* This device consists of hinged flaps, which are connected to a common frame. This is also under development in Norway. The maximum power in the simulations is assumed to be 1200 kW per device.

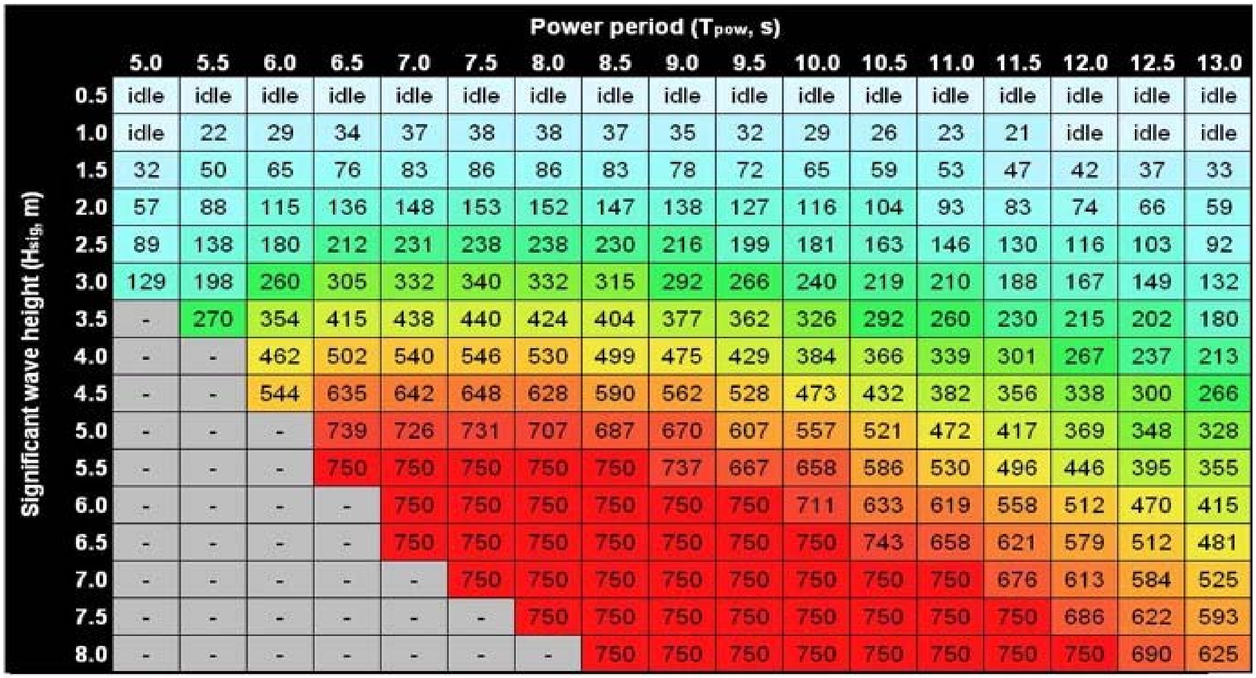
---

[2] Babarit A., Hals, J., Muliawan M.J., Kurniawan, A., Moan T., Krokstad, J., 2012. Numerical benchmarking study of a selection of wave energy converters. Renewable Energy 41, 44-63.

- *Floating oscillating water column:* This is a backward bent duct buoy with a submerged opening aligned downstream of the waves. A device of this type would typically be constructed of thin walls enclosing a water column. The movement of the column creates oscillating pressure in a chamber in which an air-driven turbine powers an electric generator. This is currently under development in Ireland. In the simulations, the maximum power per device was assumed to be 2900 kW.

Simulating Electrical Power Output

Wave energy converter energy production can be calculated by means of conversion matrices that relate wave height and period to power output, in kilowatts. The conversion matrix for the Pelamis wave energy converter is illustrated in Figure 3. The maximum power generated by the current design is 750 kW at significant wave heights greater than or equal to 5.5 meters. The relationship to the wave period is nonlinear. The power flow peaks for intermediate values of the period, but declines at higher values. At a significant wave height of 5.5 meters, the Pelamis generates the maximum power for periods between 6.5 and 9.5 seconds. At greater values of the height, the maximum is reached for values of the period up to 12 seconds. In the simulations for the Pelamis and the other devices, the resolution of the matrix was increased to 0.1 meters, using linear interpolation.



Significant wave height (H_{sig}, m)	Power period (T_{pow}, s)																
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

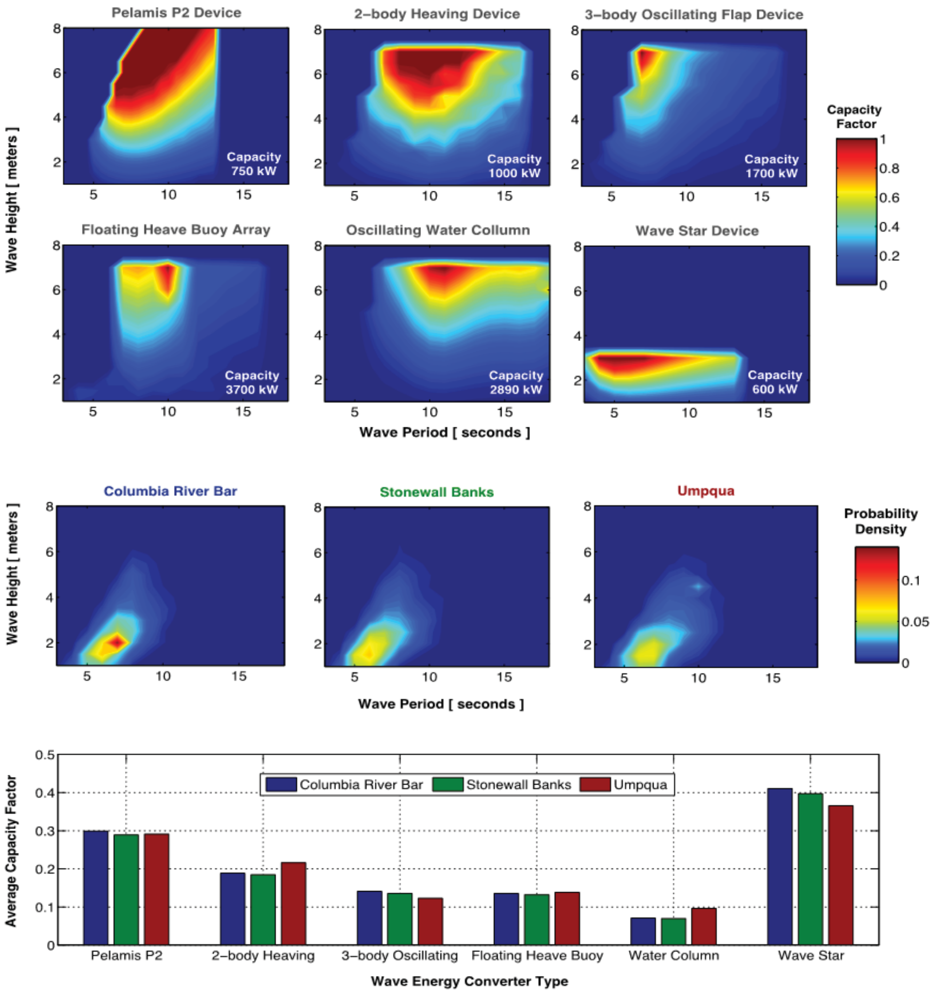
Figure 3: Conversion matrix for the Pelamis wave energy converter (www.pelamiswave.com)

The actual power output of a wave energy plant will be less than the flux because of electrical, hydraulic and mechanical losses and because a practical WEC will produce power only up to its rated capacity. This rated capacity differs depending on the machine and is determined by the economics of machine design and site characteristics.

The relationship of WEC performance characteristics, as described by the conversion matrix, wave characteristics at a given site and the resulting energy production is illustrated in Figure 4. At the top of Figure 4 are representations of the conversion matrices of the six WECs considered in this study. Rather than showing the power output as kilowatt values, the output is represented as color values, ranging from dark blue (little, or no output) to deep red (output at rated capacity). The resulting shapes suggest the type of wave environment in which each WEC will be most productive. The peak response of the Pelamis (upper left matrix), for example, is to waves of moderate to high amplitude (height) and moderately-short to moderately-long periods. In contrast, the Wavestar (lower-right matrix), responds well to low-amplitude waves of short to moderate periods.

The three plots in the center of Figure 4 illustrate the characteristic wave amplitude and period of three of the NDBC stations used for this study. The axes of these plots represent wave height (vertical) and period (horizontal) on the same scales as the axes of the six conversion matrices. Blues represent infrequent occurrences of height and period values and reds higher probability occurrences. The three buoy station plots demonstrate similar wave characteristics – high probability of low amplitude waves (relative to the most productive amplitude of most of the WECs) and moderately-short periods.

Visual comparison of the converter matrices and the plots of site characteristics suggests the Wavestar would likely be the most productive machine for each of these sites. This is confirmed by the bar charts at the bottom of the figure showing the estimated annual capacity factor of the six WECs at each of the three sites, based on calculated output using the numerical wave data and conversion matrices. The Wavestar (right-hand cluster of bars) does produce the highest capacity factor for all three sites. However, the Wavestar, limited to shallow depths, would be suitable only for the Columbia River Bar site. The Pelamis yields the highest capacity factor of the five deep water WECs for the two deep water sites, and performs reasonably well for the shallow site, as well.



Power output characteristics of 6 wave energy converters at different wave period and height

Figure 4: WEC conversion matrices plus site-specific wave height and period data yield electric energy production

The WEC electric power output differs from the wave energy flux in several ways. First and most importantly, they are in different units. The flux is in kW/m of wave crest, while the power output is in kW. Second, the power output is not calculated as a function of the flux, but rather as a function of the wave height and period. Third, the relationship between the wave height and period and the power output is clearly nonlinear. As the wave height increases, the power tends to level off. As the wave period increases to about 10 seconds, the power output increases. However, the power output peaks as the wave period reaches a particular threshold, usually around 10 seconds. As the wave period increases to more than this threshold, the power output declines. For example, the power output of the Pelamis device peaks when the wave period lies in a range of 10-12 seconds.

The simulated power series are reported in the following five hourly databases posted at www.oregonwave.org:

- Pelamis is the power output for the Pelamis P2 device.
- Power 1 is for the Wave Star device.
- Power 3 is for the floating two-body heaving converter.
- Power 5 is for the floating heave buoy array.

- Power 7 is for the floating three body oscillating flap device.
- Power 8 is for the floating oscillating water column.

Figure 5 below denotes the seasonal variability of the wave resource of representative WEC power outputs and the electric load of the BPA system. Although from a regional perspective, the wave resource and load requirements do not perfectly align, from a local perspective the potential output tracks more closely with local coastal loads, where early projects will serve.

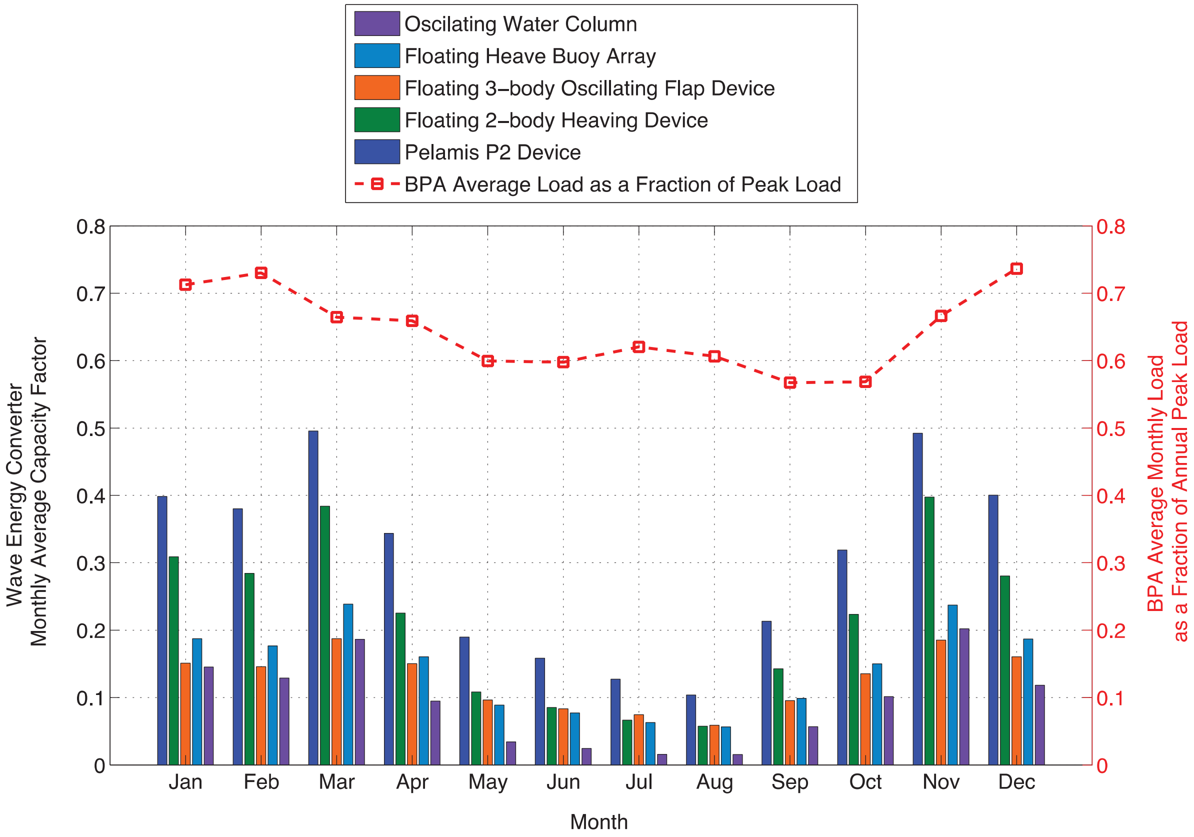


Figure 5: Seasonal patterns of wave energy converter power production and electrical load in the Bonneville Power Administration balancing area in 2011

III. Forecasting Wave Energy Converter Output

The ability to forecast future electricity generation is a critical economic and planning consideration for a utility. The focus of this study is the accuracy of near-term forecasts (minutes to tens of hours). These forecasts affect the amount and cost of operating reserves needed for system integration. To better understand the 'forecastability' of wave energy, two types of forecasting models, statistical models and physics models were evaluated to determine their respective accuracy as a function of time horizon. Statistical models include the persistence forecast (setting the forecast equal to the most recently observed values), and more advanced techniques such as regressions and neural networks. Physics models are large scale models, which incorporate wind forecasts, and use these to drive a forecast of wave characteristics. Physics models have been in operation since the 1960s, and have evolved substantially since this time[3]. Prior work indicates that the choice of physics versus statistical techniques depends primarily on the forecast horizon. Statistical models can predict waves more accurately at horizons of 1-5 hours, while for longer horizons physics-based models have been found to be more accurate. Combining both methods has been found to predict more accurately than either one individually for all time horizons[4].

Statistical Models

Forecasting experiments using a nonlinear regression model with time-varying coefficients were set up as follows. The first 500 observations were used as a training sample. The power series were then forecasted iteratively. In each instance, the regression models were estimated over prior values, forecasted, then re-estimated over the most recent value, etc. All the forecasting is dynamic. All the predictions are true out-of-sample forecasts, in that they use only data prior to the start of the forecast horizon. The forecasts are for horizons of 1-6 hours. All the intervening periods are omitted. In other words, for horizon t+2, the forecasts for t+1 are excluded.

At the deep water sites, the forecasts are for the wave energy flux, and the power output of the Pelamis, and the four devices under development. At the shallow water sites, the forecasts are for the wave energy flux and the power output of the Wavestar. The forecast error is calculated as the mean absolute percent error (the absolute value of the forecast less the actual, divided by the actual).

There are several notable findings, illustrated in Figure 6. First, the most predictable power series are the Pelamis, the heaving buoy array, and the three-body oscillating flap device. These all show consistently lower forecast errors than the flux, at all horizons. The errors for the Pelamis, the heavinge buoy array and the 3-body oscillating flap device are extremely similar. In each case, the forecast error is in the range of 9-11 percent at 1 hour, increasing to about 25 percent after 6 hours.

By comparison, the forecast error for the two-body heaving converter is somewhat higher, and quite similar to the flux. The error at 1 hour is about 13 percent, surpassing 30 percent at 6 hours. The oscillating water column is consistently less predictable than the flux, with much higher forecast errors than the other devices.

---

[3] Hasselmann, K., Ross, D.B., Müller P., Sell, W., 1976. A parametric wave prediction model. Journal of Physical Oceanography 6, 200–228.Hasselmann, D.E., Dunckel, M., Ewing, J.A., 1980. Directional wave spectra observed during JONSWAP 1973. Journal of Physical Oceanography 10, 1264–1280. Snyder, R.L., Dobson, F.W., Elliott, J.A., Long, R.B., 1981. Array measurements of atmospheric pressure fluctuations above surface gravity waves. Journal of Fluid Mechanics 102, 1–59., Janssen, P.A.E.M., 1991. Quasi-linear theory of wind-wave generation applied to wave forecasting. Journal of Physical Oceanography 21, 1631–1642. Janssen P.A.E.M ., 2007. Progress in ocean wave forecasting. Journal of Computational Physics. 227, 3572-3594.

[4] Durrant, T.H., Woodcock, F., Greenslade, D.J.M., 2008. Consensus forecasts of modeled wave parameters. Weather and Forecasting, 24, 492-503. Woodcock, F., Engel, C., 2005. Operational consensus forecasts. Weather and Forecasting, 20, 101-111. Woodcock, F, Greenslade, D.J.M., 2006. Consensus of numerical forecasts of significant wave heights. Weather and Forecasting, 22, 792-803., Pinson, P, Reikard, G, Bidlot, J.R., 2012. Probabilistic Forecasting of the Wave Energy Flux. Applied Energy. 93, 364-370. Reikard, G., Pinson, P., Bidlot, J.R., 2011. Forecasting Ocean Wave Energy: The ECMWF wave model and time series methods. Ocean Engineering. 38, 1089-1099.

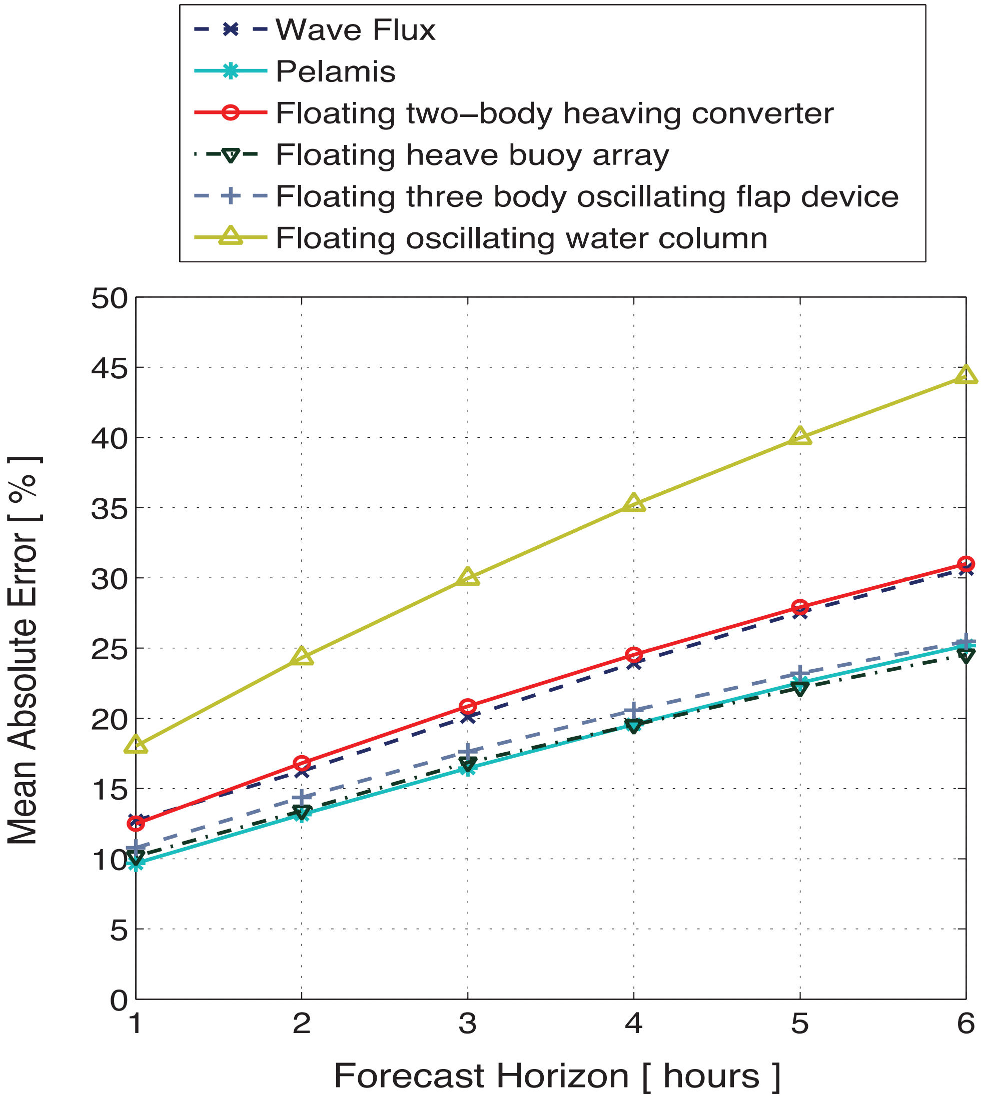


Figure 6: Forecast error for the wave energy flux and power output of five wave energy converters for a deep water site using a nonlinear regression model

Second, in shallow water, the forecast error for the flux is small at short time horizons, but it increases very rapidly, so that at a horizon of 6 hours, the error is about the same as at the deep water sites. At the two shallow sites, the error for the Wavestar is much lower than the error for the flux. It is less than 10 percent at 1 hour, increasing to over 25 percent at 6 hours. The forecast error for the flux is closer to 13 percent at 1 hour, surpassing 30 percent at 6 hours.

Another interesting finding is that the forecast error does not vary much by season. At first sight, one might anticipate that the errors would be higher in winter, given greater wave height and stormy conditions. However, since the power output stabilizes at the WEC rated capacity, the power output is often just as predictable in winter as in summer. Instead, the winter error exhibits two properties. It is rather high on average, and it exhibits intermittent extreme values. These outliers typically occur at transition points between volatility and quiescence, which are common in all seasons.

Physics Models

The large-scale physics models use an entirely different approach. Waves are forced by wind, and are influenced by wave-wave interactions, and wave dissipation. In other words, the physics model uses a wind forecast, along with equations to predict the dynamics of waves, rather than the wave data per se. There are several physics-based models that can be used for wave simulation and forecasting. These include two large-scale models, WAVEWATCH III, and the European Center for Medium-range Weather Forecasts (ECMWF) wave model, and one smaller scale model, SWAN (Simulating Waves Near Shore).

To evaluate the physics-based models, selected forecasts generated by WAVEWATCH III were compiled. Recently, a forecasting system for the Pacific Northwest was established at Oregon State University. The Northwest National Marine Renewable Energy Center website provides additional documentation on the project (http://nnmrec.oregonstate.edu). The files were made available by the Oregon State University professors involved in the project. The WAVEWATCH III model is owned and operated by the National Oceanic and Atmospheric Administration's National Weather Service: http://polar.ncep.noaa.gov/waves/index2.shtml.

This model is run every 12 hours. However, due to the number of files involved, 72 forecasts per data buoy station were extracted. These cover the period from October 2011 through December 2012. The forecast horizons range from 1 through 84 hours. The forecasts from the physics model were then compared with the actual values. The error was again calculated as the mean absolute percent error.

The behavior of the forecast errors of the physics-based model is very different from those in the statistical models. At the three deep water sites, the errors for the flux average in the range of 44 to 55 percent, at all horizons. What is remarkable about the physics models is that there is no particular change in accuracy associated with the length of the forecast horizon. The model is roughly as accurate at the 1 hour horizon as it is at 6 and 12 hours, and all horizons beyond this. This is in striking contrast to the regression model error, which is smaller over short horizons, but increases rapidly as the horizon extends.

The findings for the shallow sites differ marginally. At Clatsop Spit, the physics model is somewhat more accurate, with the error in the range of 33 to 44 percent for the flux, and 26 to 32 percent for the Wave Star power output (Figure 6). However, at Grays Harbor, the model is much less accurate, and significantly less accurate than for the deep sites.

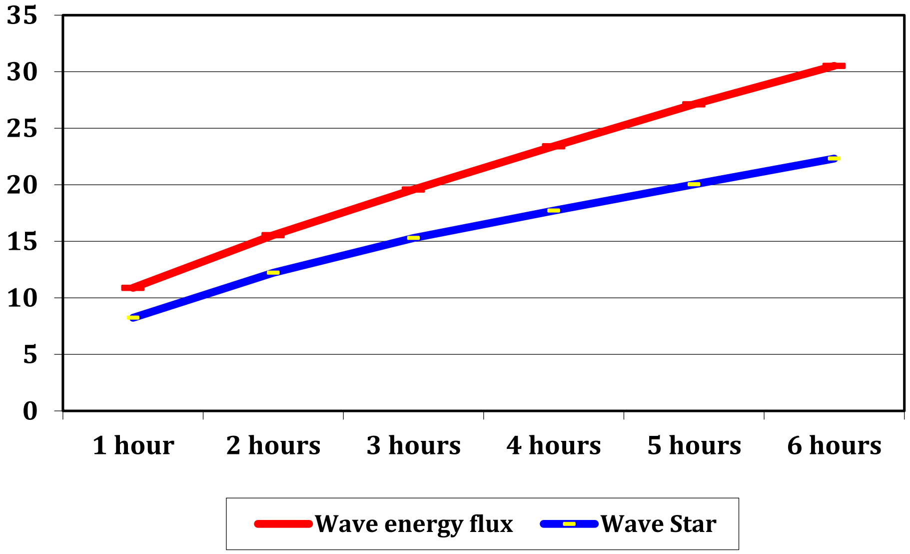


Figure 7: Forecast error for the wave energy flux and the power output of a Wavestar wave energy converter at a shallow water site (Clatsop Spit) using a nonlinear regression model

Additional tests were run, in which the regression models were extended out to longer horizons. The convergence points, at which the regressions and physics models yielded comparable degrees of accuracy, were in the range of 10-12 hours for the deep water sites. They were somewhat shorter (about 6 hours) for Clatsop Spit, but longer for Grays Harbor.

Comparing the physics model with statistical techniques demonstrates that the statistical time series methods are significantly more accurate over short horizons, generally 1-10 hours, often longer. However, as the forecast horizons extend, the accuracy of the two techniques converge. Over long horizons, generally 12 hours and above, the physics model is more accurate. By implication, statistical methods are better adapted to estimating reserve requirements, buying and selling power in markets, and peak load matching. Physics models are better adapted to long-term planning and simulation. The physics model does however offer one major advantage. It makes it possible to simulate and predict waves over a wide range of locations, including locations where there is no buoy data.

Recommendations Regarding Forecasting Methods

Prior tests have found that statistical methods are more accurate over short horizons, on the order of 1-5 hours. However, the error increases sharply as the horizon increases. Physics models on the other hand predict more accurately over longer horizons. Statistical models offer the most accurate forecasts for time horizons relevant to operational planning, including estimating reserve requirements, whereas physics based models are better adapted for longer-term decisions such as unit commitment for large energy facilities.

IV. Wave Energy Integration Cost and Issues

Wave energy presents similar challenges as other types of variable renewable resources: the generation is variable, control of the output is limited (e.g., only downward), and output cannot be predicted with a high level of certainty. These are the attributes that result in what are called “integration costs”. The power system must generally hold reserve generation capable of quickly increasing (“inc reserve”) or decreasing (“dec reserve”) output to balance the renewable resource output when it varies from its predicted (“scheduled”) levels[5]. Integration costs are generally associated with holding and operating reserve generation[6]. Calculating integration costs boils down to determining the amount of needed reserve generation, and the cost of holding and operating those reserves.

As simple as that may sound, both the amount and cost of reserves depend on a range of factors. The quantity of needed reserves depends strongly on:

- The variability of the resource (affected by the quantity and location of the generation).
- The size of the balancing authority area (BAA) into which the resource is integrated.
- The interconnectivity of the BAA with neighboring BAAs.
- Market structure of the interconnected grid.

Similarly, the cost of reserves is dependent on multiple factors as well:

- Type of resources providing reserves.
- Fuel prices (primarily natural gas).
- Wholesale electric market prices (depends on natural gas prices, load growth, etc.)

This wide range of variable factors makes it difficult to assess a single integration cost for wave energy. One approach would be to repeat the analysis over a number of scenarios to develop a range of costs. However, stakeholders consulted for this project were more interested in receiving time series of potential wave energy generation to enable them to produce integration costs themselves, with their own sets of assumptions. In response, integration costs for a single scenario were calculated for illustrative purposes: 500 MW of wave energy connected to The Bonneville Power Administration (BPA) system using 2014 BPA rate case reserve costs. Beyond that, the project concentrated on providing wave energy resource generation time series to be made publicly available.

As described earlier, five sites have been identified for developing future wave energy resources along the Oregon Coast. Figure 2 shows the approximate locations of the chosen sites. Ideally, long period (i.e. years or decades) of ocean observations would be used to develop estimates of the behavior of future wave energy generators located at these sites. Though the NDBC buoys are not located near the proposed development sites, wave characteristics are sufficiently correlated to allow NDBC buoy data as

---

[5] Reserves are required to balance all variations from scheduled operations, including variations in demand and other generators in the system. Integration costs are associated with additional need for reserves associated with adding variable renewable resource generation.

[6] Other costs are sometimes explored such as those relating to day-ahead purchases of power or fuel, but most studies find those costs to be minimal or non-existent.

the basis for forecasting prospective wave plant output. Figure 1 shows the locations of NDBC buoys along the Oregon/Washington coastline.

The NDBC buoys collect wave height, period, and direction data that can be used to estimate generation from wave energy devices. Buoy data has been collected over a number of years, generally reported in hourly or half-hourly increments. While buoy data has the advantage of representing actual ocean wave measurements, several challenges around using the data emerged:

1. The data suffers from substantial gaps in time (missing data) for many of the years of record.
2. Observation sites are not coincident with development sites.
3. Data on finer timescales (less than 15) is better suited for this type of analysis.

A relatively full set of data for the five NDBC buoy stations existed for 2010. Although the buoy sites were not co-located with the development sites, there is a very high degree of correlation among the sites. It was felt that a reasonable approximation of integration costs could be made from the buoy data if a method could be found to synthesize sub-hourly data from the hourly observations.

Creating Intra-Hour Data Sets

Translating hourly wave observations into sub-hourly periods is based on using measured wave height period and direction information to assemble a full directional spectrum based on Texel, Marsen, and Arsloe (TMA) spectrum. The method then associates hourly wave height, period and direction data into a spectrum of sinusoidal waves of different frequencies with pre-determined amplitudes. The collection of waves is a mathematical representation of water surface elevations in time and space around the observation site. Surface elevations through time can be computed for a matrix of nearby wave energy converters. The square of the surface elevation velocity is taken to be proportional to the energy available at each of the wave energy converters and can be computed at any desired time scale. This procedure does not return the actual wave elevation from the historical period, but seeks to capture the statistical characteristics of wave behavior.

As it turned out, researchers at Oregon State University (OSU) had developed a computer model[7] that takes hourly values of wave characteristics and produces equations that characterize wave surface elevations in time and space around the measurement sites. OSU researchers graciously offered the intra-hour model for use in this project. Hourly wave height, period, direction and sea floor depth were entered into the model. Using a simple representation of a wave energy conversion device (output proportional to the square of the ocean surface velocity), the model produced minute-by-minute energy generation for a field of wave energy converters around the buoy sites. A combination of buoy station data and the OSU intra-hour model enabled producing data sets from which reserve requirements could be determined, and an estimate of integration costs calculated from BPA reserve costs developed in their 2014 rate case.

OSU researchers had also developed a data set representing hourly wave conditions across the Oregon Coast using a combination of numerical weather prediction and wave propagation models known as Wavewatch III[8]. OSU's Dr. Özkan-Haller and Mr. Garcia-Medina offered to make model output available

---

[7] T. Brekken, H. T. Özkan Haller, A. Simmons, *A methodology for large- scale ocean wave power time-series generation*, IEEE Journal of Oceanic Engineering 37 (2) (2012) 294–300.

[8] Garcia-Medina, G., Özkan-Haller, H.T., Ruggiero, P., and Oskamp, J. (2013), *An Inner-Shelf Wave Forecasting System for the US Pacific Northwest*. Wea.Forecasting. doi:10.1175/WAF-D-12-00055.1.

for years 2007-2010 at a 30 arc-second geographic resolution. This enabled development of a longer-term quasi-historical data set that might be used to represent data at prospective development sites. The OSU model wave data was used in conjunction with the OSU intra-hour model to represent wave energy device output over a range of development levels (megawatts per development site), averaged over various time periods (1-minute, ten-minute, 60 minutes) for public use.

The hourly weather/wave model data exhibited statistical characteristics different from the observed data. The model over-estimated the available wave energy resources when model output was compared to buoy data for 2010. Model output showed higher correlations among buoy locations than the observed data, and the model representation of wave period was significantly different from the observed buoy station data—the model updated wave period every three hours, missing hourly variability. The results of the model were transformed to maintain a reasonable representation of the seasonal resource shape over 2007-2010 while maintaining statistical characteristics of the buoy observations. The transformation method is described more fully below.

Capacity Factor

The capacity factor of a power plant is its average output divided by its maximum capability. Some typical capacity factors for NW resources:

- Hydro 45%
- Wind 30%
- Nuclear 80%

The capacity factor is derived from a combination of factors for renewable resources. The availability of the raw resource (waves, sun, wind) is an important factor, but not the only one.

For example, Bonneville Dam has more than 1,000 MW of generating capability but produced just 460 megawatts on average in 2010, for a capacity factor of 46%. If instead of 1,000 MW of capability, it had a single 500 MW generator, that generator would be kept busy nearly all the time (except for maintenance)—near 100%. There would be an economic tradeoff in lost energy through most of the year when stream flows are in excess of the turbine’s capability. Capacity factor is largely an economic choice, for example the number and size of turbines at Bonneville Dam.

This is a practical issue for determining characteristics of wave energy devices. We can calculate the available wave energy density, but the actual production depends not only on the wave resource, but also on the size of the wave energy converter device and its efficiency relative to the size of the generator. For the integration cost analysis a conversion factor was assumed that reproduced an annual capacity factor of about 30%

To summarize, hourly buoy station observations were used to estimate the integration costs of a total of 500 MW of wave energy converters located in separate arrays of 100 MW at each of the five NDBC buoy sites[9]. Each of the five sites was assumed to consist of 100 wave energy converters with a maximum output of 1 MW each. Longer-term (2007-2010) time series of intra-hour generation data were developed from OSU’s weather/wave model for the envisioned wave energy development sites. Observed data was used to adjust model output to better represent the characteristics expected at the development sites.

---

[9] The integration cost estimate was based on data from NDBC buoy stations, not the anticipated development sites because of the availability of direct observations at the buoy sites, and because of the high degree of correlation of buoy data along the Oregon Coast.

Calculating Reserve Costs

Integration costs are the combination of reserve requirements needed to accommodate the variability and uncertainty of a variable resource, and the cost of holding and deploying those reserves. Determining the level of increased reserves needed involves assuming a base system with existing variability (other variable resources and loads) and adding the variability from the new resource. Reserves are held to meet system reliability requirements—generally levels are established to meet a large fraction (95% for many balancing authorities, but 99.5% in the case of the Bonneville Power Administration balancing authority, that serves much of the Oregon Coast) of the variability. As the variability increases, the level associated with the reliability requirement increases. The incremental change to maintain the defined reliability may be attributed to the added resource.

This analysis used data made available by BPA that corresponded to the variability on their system in 2010. BPA is a relatively large wholesale power system with some 15,000 miles of high voltage transmission lines, more than 20,000 MW of hydro, roughly 4,500 MW of wind generation, and several thousand megawatts of thermal resources interconnected to their system[10]. BPA made minute-by-minute data for 2010 available to this project. The data represented deployment of reserves to cover the unscheduled variations on their system due to deviations from expected load and resource performance in each hour. The base reserve level was set at a quantity that encompassed 99.5% of all deployments for the year.

Estimating the additional reserves needed to integrate 500 MW of wave energy included the following steps:

1) Develop a time series of wave energy generation on 1-minute intervals.
2) Produce a schedule[11] of wave generation from forecast output for each hour.
3) Take the difference in 1) and 2) and add it to the base reserve deployment time series supplied by BPA.
4) Find the new 99.5 percentile level for the result in 3).
5) Take the difference between 4) and the base reserve level to find the incremental reserve requirement.

The result is the additional reserves needed to maintain a 99.5% reliability standard.

BPA divides the total reserve requirement into three categories representing the timescale on which reserves must be deployed:

- Regulation (representing variations occurring within 10 minute periods)
- Following (variations from each 10 minute period to the next)
- Imbalance (accounts for variations from each hour to the next)

---

[10] From BPA Fast Facts 2013: http://www.bpa.gov/news/pubs/GeneralPublications/gi-BPA-Facts.pdf

[11] The schedule is identical to the forecast except that the schedules are “ramped in” during the first and last ten minutes of each hour.

The steps identified above were undertaken using hourly buoy station observations from 2010, converted to one-minute data using the OSU intra-hour model (step 1 above). A persistence forecast was used to produce wave energy schedules for each hour. Persistence forecasts are a simple form of a statistical model in which the actual generation at one time is taken to be the forecast for a later time. In this analysis, the average generation over the hour ending one hour prior to the start of the scheduling hour constituted the forecast—for example, the average of the first 60 minutes of generation for a day were taken as the forecast for the average generation over minutes 121-180.

The persistence forecast methodology was used because the improvements seen in the previous section for more complex methods were modest and justified the ease of implementing persistence forecasts. Persistence forecasts are often used in the creation of wind generation schedules and represent a good baseline assumption.

The development of the forecast and schedule deviations is illustrated in Figure 8. In Figure 8, the difference between "Actual Wave Generation" (in orange) and "Wave Generation Schedule" (solid blue line) are added to similar variations in other components of BPA's system (including demand) to develop reserve requirements. Note that the schedule is developed from the hour-average wave energy generated sixty minutes prior to the start of each scheduling hour.

Differences between the resulting schedule and the observations were calculated as in step 3) above. The new variability was combined with the existing base case reserve deployments and the results displayed in Table 2. In Table 2, incremental reserves represent the additional need for generation that can be increased on short notice and decremental reserves are the added need for generation that can be reduced on short notice. The values are predicated on meeting 99.5% of all variances from schedule with available reserves.

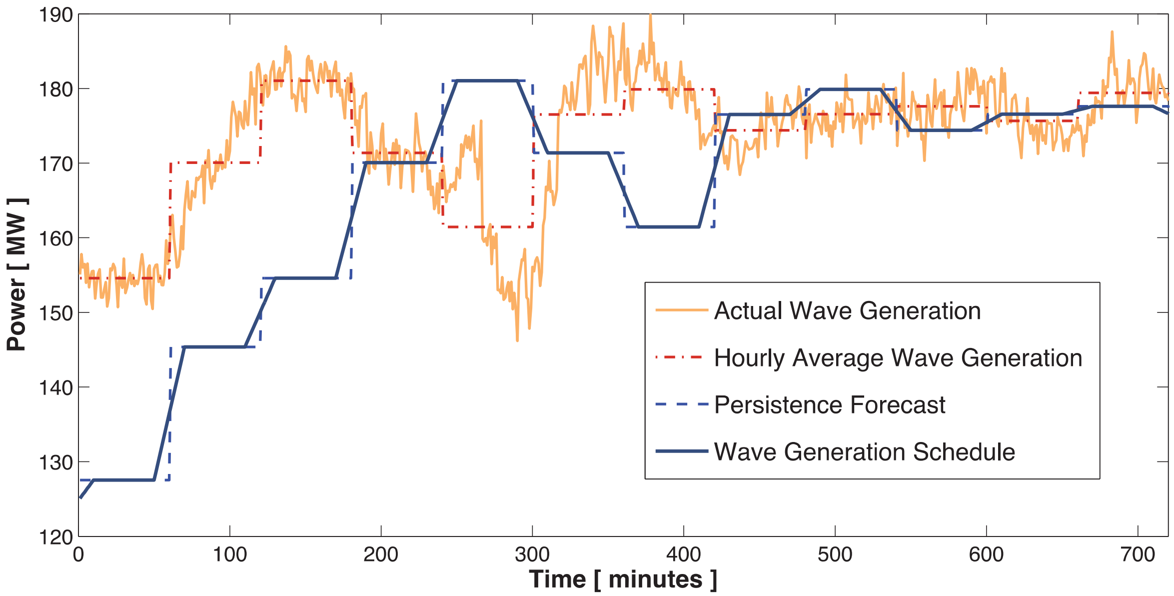


Figure 8: Illustrating the derivation of wave energy variations for calculating reserve requirements

Reserve Type	Incremental Reserves (MW)	Decremental Reserves (MW)
Regulation	1	-1
Following	2	-2
Imbalance	5	-5

Table 2: Additional reserve requirements on the 2012 BPA system after adding 100MW of WEC capacity at each of the five NDBC stations

Reserve requirements identified in Table 2 can be converted into integration costs given the cost of the corresponding types of reserves. BPA identifies the costs of providing reserves in its rate case proceedings. Table 3 shows the costs BPA developed in their most recent 2014 rate case[12].

Reserve Type	Incremental Reserves ($/kW-month)	Decremental Reserves ($/kW-month)
Regulation	$7.60	$0.57
Following	$7.42	$0.58
Imbalance	$7.17	$0.62

Table 3: Reserve costs from BPA 2014 Rate Case

Applying the price per unit of reserve capability in Table 3 to the requirements in Table 2 returns a raw cost of supply reserves to the assumed 500 MW of wave generation. Wind project operators on BPA's system are charged for balancing reserves on a installed capacity basis. The same can be done for the wave resource for comparison purposes. The operation just described results in a wave energy charge of about $ 0.09 /kW-month of installed wave generation. This compares to the BPA wind integration charge of $1.20/kW-month[13]. In other words, the cost of integrating 500 MW of wave energy would be less than a tenth that of wind energy per unit of wind or wave generation basis. It should also be noted that BPA uses a more complex cost allocation methodology than the incremental reserve method described here, but these results should be reasonably representative.

This analysis is approximate, and as described previously, depends on a number of factors—not least important of which is the relatively large size of BPA's system and its existing fleet of variable (i.e., wind) resources. The addition of 500 MW of wave energy introduces a relatively small amount of additional

---

[12] *BP-14 Initial Rate Proposal Generation Inputs Study* (BP-14-E-BPA-05), Bonneville Power Administration (2012), and *BP-14 Initial Rate Proposal - Generation Inputs Study Documentation* (BP-14-E-BPA-05A-E01), Bonneville Power Administration (2012)

[13] In its 2014 rate case, BPA developed a range of potential charges depending on the accuracy of the schedule, and selection of schedule duration (60 minute, 30 minutes, 15 minutes). The comparison figure most closely aligns with the methodology used to develop the values in Table 2.

hour-to-hour and minute-to-minute variation used to develop reserve requirements. A smaller system could see a significantly larger effect as the wave variability could dominate existing variability on the smaller system.

It is interesting to note the difference between the intra-hour model generation results compared with the flux. Figure 8 shows a comparison between hourly averages of the 1-minute generation data and hourly flux figures from buoy station observations. Although there is a strong correlation between hourly flux and wave generator output, flux from the buoy observations exhibits a much wider dynamic range that the intra-hour model output.

A concrete example can be taken from the data in Figure 8. The flux in hour 3870 was 31 kW/m and the average generation across 50 wave generators for the model was .57 MW. In contrast, in hour 8084 the flux was 240 kW/m, almost 8 times as high, but the simulated generation from 50 generators averaged just .71 MW, or just 25% higher. Significantly, none of the 50 simulated generators was at its maximum (1 MW) capability in either hour.

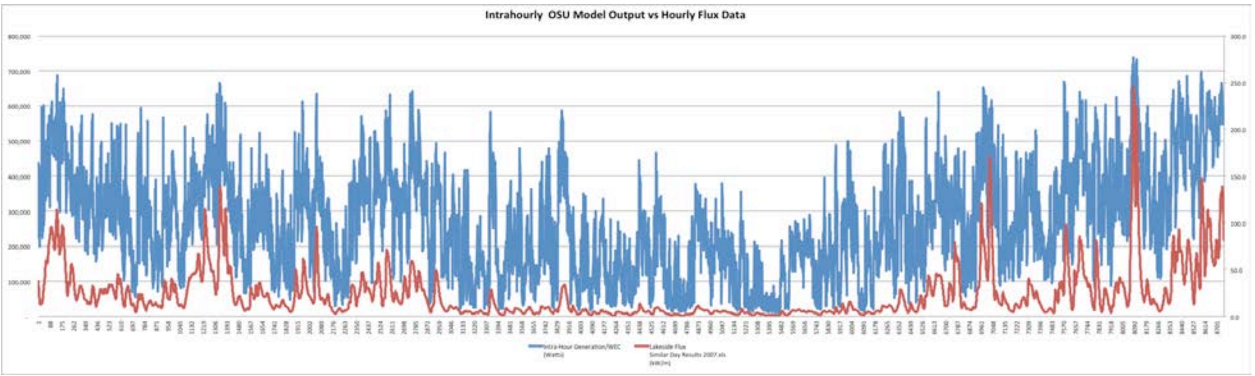


Figure 9: Illustrating the relationship between the intra-hour model simulated generation levels (blue) and flux calculated directly from the 2010 Lakeside buoy observations which were input to the model.

The data depicted in Figure 9 shows the model output introducing more hourly variability than exists in flux based on the single buoy station observation, but less dynamic range over widely varying ocean conditions. A likely reason for some of the difference between these curves has to do with the representation of the wave energy converter devices versus the theoretical energy availability from the flux equation: $E_{Ft} \approx 0.4907 (H_{St}^2 T_{Mt})$. The equation shows flux increasing in proportion to the wave period. Real wave energy converters will not likely respond in that manner—in the limit of very long-period waves, the resource acts more like a tide than a wave. Many energy converters will not respond to that component of the wave energy very well.

This can be seen in the Pelamis power production matrix in Figure 3. For a given wave height, energy output increases with wave period up to a point, and then begins to fall. The ability of a wave energy converter to make use of the energy in long-period waves is a function of its specific design. Some wave converters may be able to make use of long period waves better than others. In other words, the very high flux peaks in figure 8 are not accompanied by a proportionate response in generation because the generators simply don't respond to much of the available energy.

In the case of the intra-hour model, the simple wave energy converter representation responded only to the vertical velocity of the surface of the wave. The energy available from that motion is inversely proportional to the wave period—energy drops with increasing wave period instead of increasing for a given wave height. This is the most likely explanation for the differences seen in the curves represented in Figure 8. Partly this is a real difference between the likely response of real wave energy converters, and partly because of the particular wave energy converter assumed in the model.

An improvement in the methodology employed would be to implement more complex representations of wave energy converters in the model.

Statistical Characteristics

Both the raw NDBC buoy data and the processed wave generation data exhibit statistics that are relevant to the cost of integrating the resources. As noted, the variability of a large collection of wave energy converters is expected to be considerably less than an equivalent amount of wind energy. Intra-hour generation data from the NDBC buoy observations was simulated from 722 wave energy converters with a maximum output of 1 MW each. This value was chosen to match the installed wind generation on BPA's system from January-October 2007. In this comparison, the wave plants were assumed to have a capacity factor of 32% to match the actual capacity factor of wind on the BPA system in 2007[14]. Figure 9 shows the variability of both wave and wind generation, albeit from different historical years (missing wave data in 2007 precluded its use). This was the most direct comparison between wind and wave energy performed.

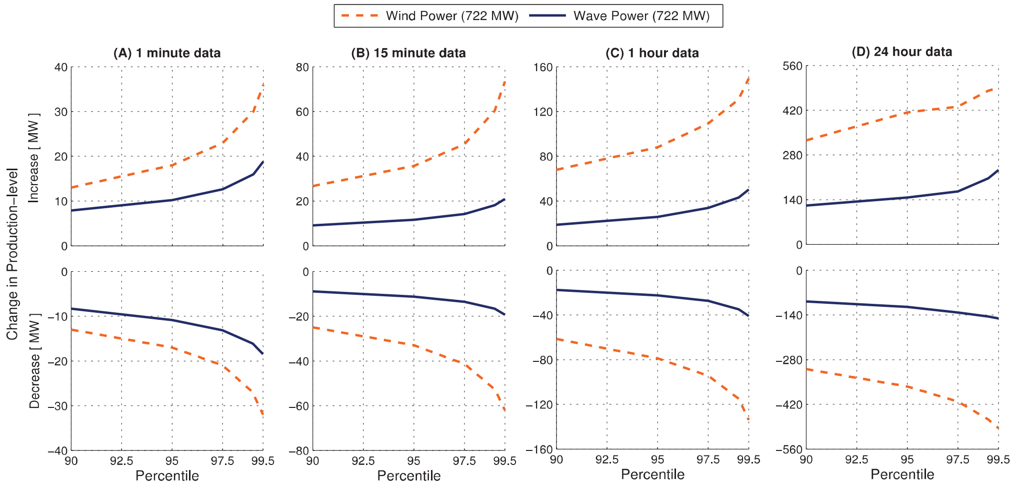


Figure 10: Comparison of the variability of 722 MW of wind generation (2007) and wave generation (2010).

---

[14] As noted previously, the wave generator capacity factor is a somewhat adjustable parameter. For this exercise the capacity factor was purposely adjusted to match the wind capacity factor on BPA's system in 2007.

Figure 11 shows how quickly variability is dampened out as individual wave energy converters are added to a single project. The further effect of dampening due to wider geographic diversity (i.e., across buoy sites) is illustrated in Figure 12. Note that the high correlation among the sites reduces the dampening effect for day-to-day variability.

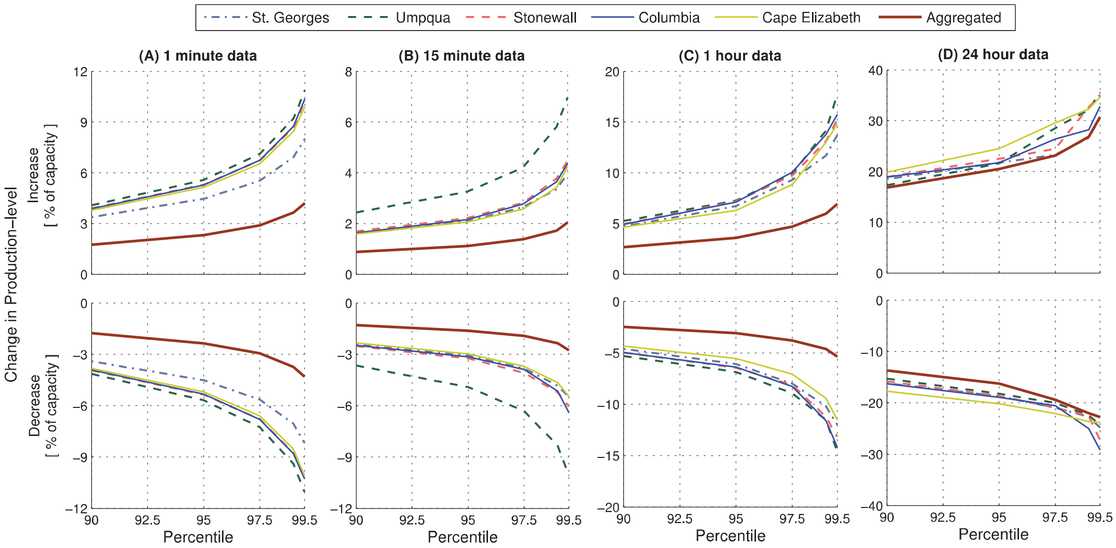


Figure 11: Variability dampening due to adding individual wave converters at a single site

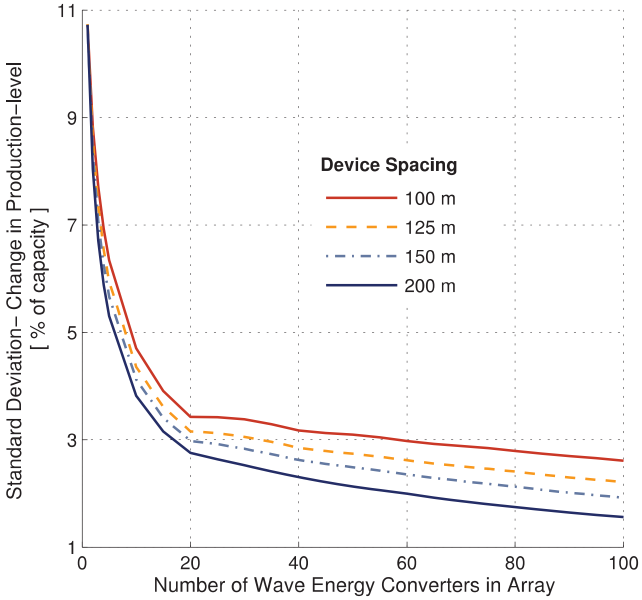


Figure 12: Dampening effect of aggregating over buoy locations

One of the striking differences between wind and wave energy is the much larger correlation among wave sites on an hourly basis. Table 4 shows the correlations in flux among the NDBC buoy stations for 2010.

Variable vs. Variable	R	R-Square
Cape Elizabeth vs. Columbia	0.94	88%
Columbia vs. Stonewall	0.92	85%
Stonewall vs. Umpqua	0.92	85%
Columbia vs. Umpqua	0.88	78%
Cape Elizabeth vs. Stonewall	0.88	77%
Umpqua vs. St. Georges	0.85	72%
Cape Elizabeth vs. Umpqua	0.84	71%
Stonewall vs. St. Georges	0.82	68%
Columbia vs. St. Georges	0.78	61%
Cape Elizabeth vs. St. Georges	0.74	54%

Table 4: Correlations in hourly wave energy flux among NDBC buoy stations

The maximum distance between the buoy stations is more than 350 miles, with a correlation of .74. Wind projects with a similar correlation would likely be within about 20 miles of each other. Figure 12 illustrates the correlation of the distant NDBC buoy stations for a few hours of sample flux data.

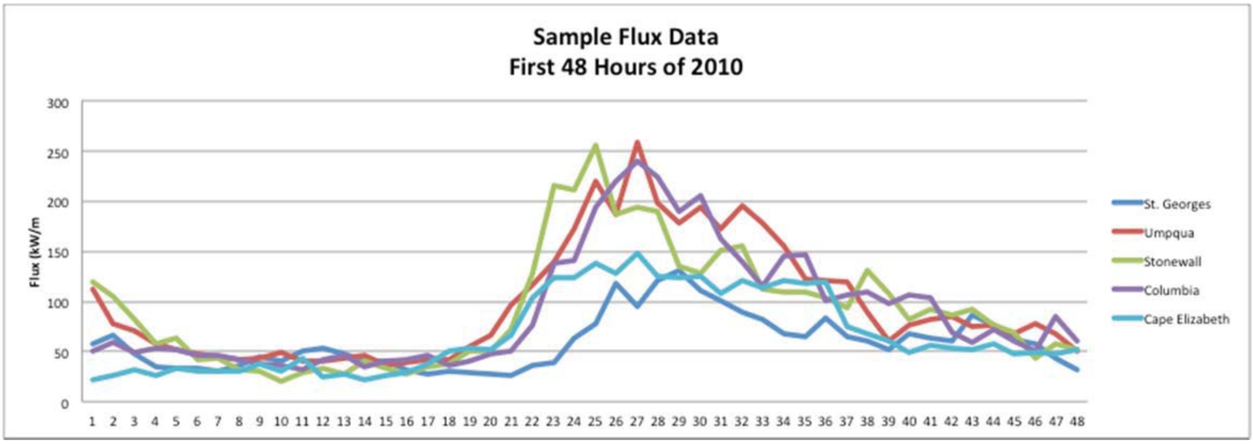


Figure 13: Sample wave energy flux data illustrating correlation among distant NDBC buoy sites

In summary, the wave energy resource appears to be significantly less variable than equivalent amounts of wind generation and the hour-to-hour correlations much higher. The latter result suggests that strategically located data collection buoys situated further off shore may provide significantly more accurate forecasts than the persistence forecast used to estimate integration costs in the previous section.

Multi-Year Synthetic Time Series at Prospective Development Sites

The NDBC buoy data for years other than 2010 contained too much missing data to be very representative. Serendipitously, OSU's Dr. Özkan-Haller and her staff produced output from a combination weather and wave model representing ocean conditions along the entire coastline for the years 2007-2010. The data was graciously provided to this project and used to represent generation at hourly and intra-hourly intervals in grid points corresponding with the prospective development sites depicted in Figure NN.

Model output for 2010 at grid cells containing the NDBC buoys was examined to compare the model output with wave observations. A number of challenges with the model output became clear:

- Hourly model output had significantly higher correlations than buoy observations.
- Model data exhibited much less variability than buoy observations.
- Wave period output looked significantly different.
- Model output over-stated the available energy compared with buoy observations.

Given these significant differences between the model output and the buoy observations, it was determined that the model output would need to be modified before it was used in the integration studies. Useful data would preserve the basic statistical characteristics of the buoy data. A multi-step procedure was developed to adjust the model data:

1) Convert output (wave height and period) to hourly flux values.
2) Adjust for observed model bias.
3) Add variability to reduce correlations among the sites.
4) Search buoy observations in six-hour windows over the same season to locate windows exhibiting similar energy and shape.
5) Stitch six-hour windows of wave height and period data together (smooth seams).
6) Use the resulting hourly data as input to the OSU intra-hour model to develop 1-minute data for wave energy converters at development sites.

The hourly flux values were adjusted by a multiplicative bias adjustment that varied randomly around the average bias. The random adjustment was chosen to reduce correlations among the sites to more closely resemble that of the buoy observations[15]. The resulting hourly figures were then used to find matching data from the 2010 buoy observations. This was done by finding the best match between the adjusted model data and buoy observations in six-hour segments. The best match was determined by finding the minimum least squares fit with the first hour and mean of the six-hour segment. Using two points for matching was done to mimic the modeled energy level and general direction (i.e., increasing or decreasing in time) of the model output. Figure 14 illustrates the procedure used to move from hourly model output to a collection of six-hour segments of buoy observations. A minimal amount of

---

[15] Model output was adjusted by a random value selected from a normal distribution for each day at each development site with a mean of 0.755 and a standard deviation of 0.1.

smoothing was employed at the seams of the six-hour segments to replicate statistics in the buoy data[16].

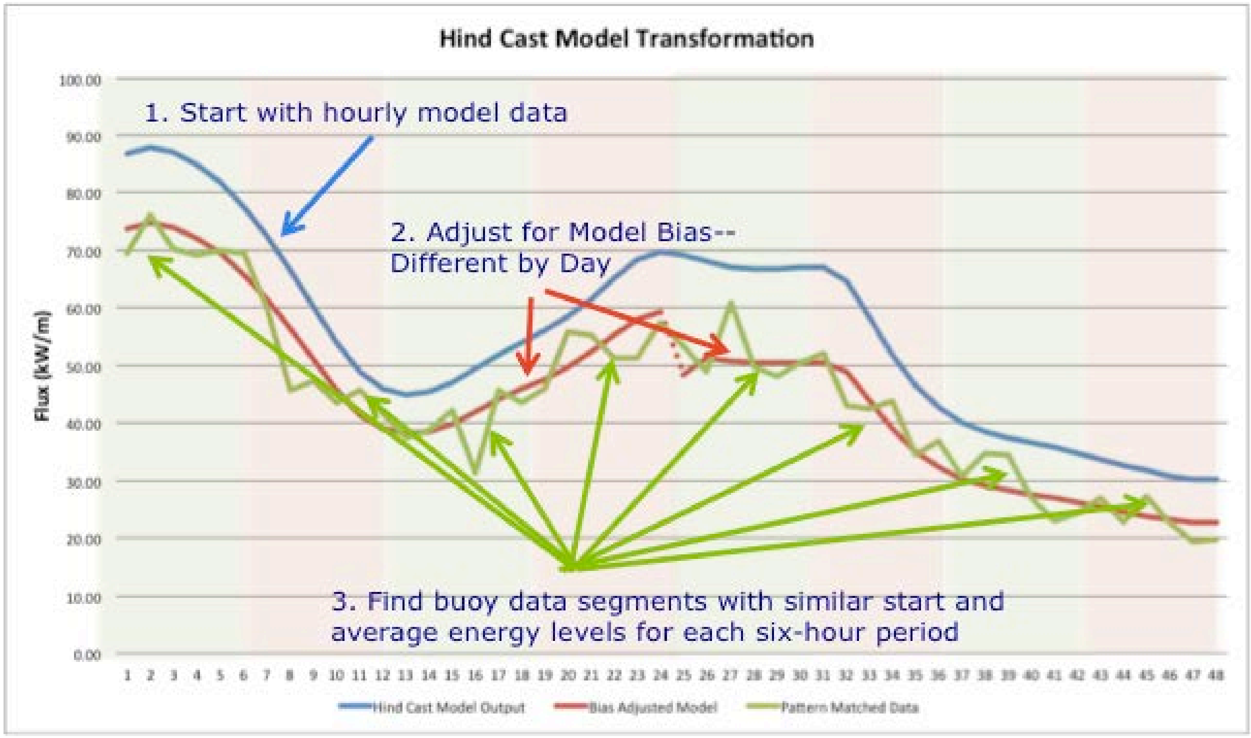


Figure 14: Illustrating some of the steps to developing hourly data at development sites from the OSU data set based on NOAA's Wavewatch III model runs with 30 arc-second grid patterns

Sample results for the Lakeside prospective development site are shown in Figure 15, reflecting annual differences in production patterns from the Wavewatch II model. Once the six-hour segments are chosen using the method described, smoothed wave height and period data from the 2010 buoy observations are stitched together to form the input to OSU's intra-hour model to get 1-minute times series for simulated wave energy converters.

---

[16] Without smoothing, changes in output at the six-hour seams ended up being over-represented in the tails of the distribution of hour-to-hour changes. This can bias (upward) reserve requirements derived from the data.

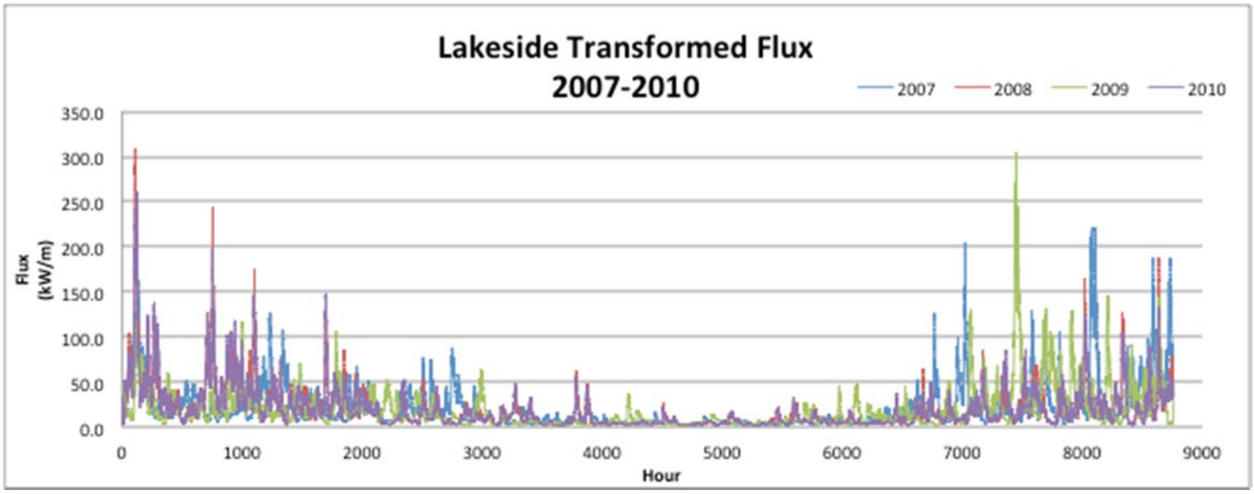


Figure 15: Flux from transformed Wavewatch III data, Lakeside prospective development site

Data was produced representing hourly flux as well as generation for up to 750 MW of wave energy converters (150 1-megawatt devices at each of five development sites) on minute-by-minute and hour-by hour bases. The intra-hour proportionality constant was adjusted to produce three sets of data representing capacity factors of 25%, 35%, and 45% (averaged over all development sites and the full 2007-2010 period). The data will be made available at www.oregonwave.org.

V. Conclusions and Recommendations

Furthering the Understanding of Wave Energy Issues

The overall purpose of this project was to provide an analysis of wave energy resources to inform utilities and balancing authorities about resource characteristics, forecasting techniques and potential integration issues and costs. This work suggests a far more modest level of integration costs associated with wave energy compared with wind energy. It found that simple persistence forecasts provide a reasonable level of accuracy for operational purposes, largely due to the substantial resource smoothing from even a few dozen wave energy converters. The study showed the seasonality of the wave energy resource, and annual variation. In short, this study demonstrated:

- Wave energy data is generally less variable than wind energy.
- There is significant benefit in aggregating individual wave energy converters in a commercial project, and across different locations.
- The wave energy resource in dispersed locations along the Northwest coast is highly correlated on an hourly basis– much more so than similarly dispersed terrestrial wind sites.
- Persistence forecasts appear to provide adequate accuracy for hour-ahead scheduling.
- Wave energy integration costs are likely to be small fraction of wind integration costs (per installed kW and kWh bases).

Advancing the Industry

This study provides strong evidence that wave energy integration is a manageable issue, and that wave energy has the potential to bring substantial value to the power grid. It shows areas where additional study is warranted and the potential for substantially more accurate resource forecasts by incorporating data from distant observation sites. The study broke new ground in using data from buoy observations, and the use of advanced computational models to develop sub-hourly data from hourly observations. The study identified the need for improvements in wave forecasting models to better capture energy aspects of wave behavior. This study has produced several major findings, including, but not limited to:

1) The wave energy potential of the Oregon coast is substantial, and largely exploitable in a conceptual context with existing and emerging technologies. However, the wave energy industry is still many years away from large scale, commercial developments. This study did not address the capital and/or operational costs (primary costs drivers) of future projects, but did demonstrate that integration costs will likely be a small fraction of the generation cost.

2) Wave energy is dominated in the long-run by seasonality (i.e., it peaks in the winter months), but in the short run by nonlinear variability. The standard measure of wave energy, the flux, is highly volatile, with large outliers at irregular intervals. However, the wave converters have the potential to smooth out the effect of large waves, so that the power flow is more predictable than the flux.

3) While wave energy can be volatile, the forecast error is generally much lower than that of wind and solar. Wind power is often dominated by large ramp events, in which power output can alternate between high and low values over short intervals. Solar power, particularly in the Pacific Northwest, is influenced by precipitation, cloud cover and atmospheric turbidity. Wave energy is considerably more stable. The predictability of waves is further enhanced by geographic dispersal. When converters are spaced out over wider areas, this tends to average out the effects of localized wave fluctuations.

4) The cost of wave energy, in terms of reserves, is considerably lower than that of wind and solar. Assuming reserves are to be calculated as a function of the 1 hour difference between actual and anticipated power, the cost of integrating wave energy could be less than half the cost of wind. However, a caveat applies here: To-date, the wave data is available at resolutions of 1 hour, or at most 30 minutes. Forecasting at shorter horizons, on the order of 15 minutes, requires interpolating the data.

Additional analysis

The study suggests the following additional analysis as desirable to better understand wave integration:

- Intra-hourly analysis could be improved. More sophisticated representation of wave energy converters is possible and could enhance the forecast and integration models.
- Additional analysis is required at higher and lower capacity factors for intra-hourly data.
- Examine buoy data for cross-correlations. For example, can one buoy forecast output at a distant buoy more accurately than using persistence forecasts?
- Examine integration requirements for different historical years (project only analyzed 2010).

In summary, waves are a promising source of energy for the Pacific Northwest. This project will help inform future development of commercial projects, where capital cost and power output associated with specific technologies can be fully validated and integrated into the Northwest power grid.

Appendix A: Stakeholder Engagement

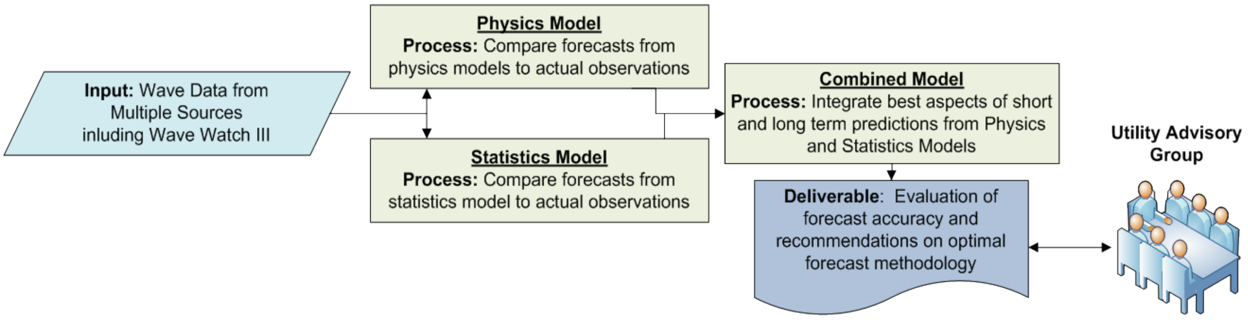
Utility advisory group models have been used extensively in the Northwest to gather input on key issues facing the industry. This project utilized 2009 Utility Advisory Group (UAG) membership as a starting point and augment with key participants from the other utility forums. This approach will promote a synergy between 1) utilities interested in wave energy, 2) balancing authorities with experience integrating wind energy, 3) balancing authorities likely to integrate wave energy in the future and 4) organizations involved in the development of the methods and approaches being used to evaluate wind.

The project team utilized the UAG to assist and direct the overall project. Members include, but were not limited to:

- Portland General Electric
- NW Power Council
- Pacificorp
- Central Lincoln PUD
- Bonneville Power Administration
- Tillamook PUD
- PNGC Power
- Eugene Water and Electric
- Douglas Electric
- Renewables NW Project

In addition to ensuring the project is of value to the utility committee, the UAG has helped the project team to:

- Review and provide input on analysis of the annual, seasonal and hourly variation.
- Review the forecast error associated with near-term forecasts (1-6 hours) developed using statistical forecasting methods.
- Discuss a physics based forecasting method being evaluated for development of longer-term forecasts.
- Provide input into key assumptions for initial estimates of integration costs using BPA's integration cost methodology.



Appendix B: Glossary and List of Acronyms

GLOSSARY

Physics-based Model: Large-scale meteorological models, generally used in weather forecasting. They show wind and weather patterns worldwide. In these models, wind forces waves. Additional equations are used for wave dissipation, wave-wave interaction, and shoaling. The equations are based on physics.

Statistical Model: These are time series equations, which are fit to individual data sets. The simplest is a persistence model, which means setting the forecast equal to the most recently observed value. More sophisticated variants include regressions on lags, and neural networks.

Balancing Authority: The responsible entity that integrates resource plans ahead of time, maintains load-interchange-generation balance within a Balancing Authority Area, and supports Interconnection frequency in real time.

Balancing Authority Area: The collection of generation, transmission, and loads within the metered boundaries of the Balancing Authority. The Balancing Authority maintains load-resource balance within this area

Reserves/Capacity Reserves: The electric power needed to provide service to customers in the event of generation or transmission system outages, delays in the completion of new resources or other factors which may restrict generating capability or increase loads. Reserves normally are provided from additional resources acquired for that purpose, or from contractual rights to interrupt, curtail or otherwise withdraw portions of the electric power supplied to customers.

Wave Energy Flux: Wave energy flux (“Flux”) is a measure of the energy of a wave. It is proportional to the square of the significant wave height times the mean wave period, and generally expressed in terms of kW per meter of wave front.

Schedule/Dispatch Schedule: The planned operating level of generators over some period of time (the “operating period”), usually an hour.

Incremental Reserves (Inc): Generation that can increase its output from scheduled levels on short notice to adjust to other variations in the system (e.g. load or variable renewable resources).

Decremental Reserves (Dec): Generation that can decrease its output from scheduled levels on short notice to adjust to other variations in the system (e.g. load or variable renewable resources).

Neural Network Model: A mathematical model inspired by simulating the neural connections in the brain. In modern statistical use, the neural net involves filtering an input data set through a sequence of sigmoid functions in order to produce an output. Neural nets can be used in forecasting, similar to regressions: in this case, the inputs are the lagged values of the time series, and the output is the forecast.

Wave Energy Converter: Any device that converts wave energy to electric power.

Significant Wave Height: Traditionally, this is the average height of the highest third of the waves. More recently, it has been defined as four times the standard deviation of the surface elevation.

Wave Period: The time it takes for two successive wave crests to pass a given point. Commonly-used measures include the mean average period (the average time), and the peak wave period (the maximum time).

TMA Spectrum: A formulation that associates relative strengths (amplitudes) of simple sine waves of different frequencies that combine to represent sea surface motions. The formulation is used to produce intra-hour time series from hourly inputs.

Capacity Factor: Average generation level of a device over some period (usually a year) divided by the maximum output level. A device with a 100% capacity factor is one that operates at full output for the entire time period.

Rated Capacity: Maximum generation level of a device under standardized conditions, often expressed as kilowatts or megawatts, sometimes as kVA or MVA.

Attenuating Wave Energy Converter: Attenuators most often lay on the surface of the ocean and capture the wave energy via hydraulics.

Point Absorber Wave Energy Converter: Point absorbers are buoy-type WECs that harvest incoming wave-energy from all directions.

Regulation Reserves: Generation that can provide Inc or Dec reserves and are responsive over time periods of less than 5 minutes.

Following Reserves: Generation that can provide Inc or Dec reserves that can respond within about ten minutes.

Balancing Reserves: Inc and Dec reserves required to maintain system reliability by responding to differences between projected and actual generation and demand on the power system.

Wave Energy Conversion Matrices: WEC matrices attempt to estimate the total electrical output of a device over a given time horizon.

Dynamic Forecasting: Forecasting over multiple periods, in which the forecast for one period is used to predict the next period. For instance, suppose one wishes to predict two hours in advance. The model predicts one hour in advance, then the forecast for one hour is incorporated into the data set, the model is re-estimated using this new data point, and the forecast for two hours is generated.

Nonlinear Regression: This includes two types of regression models. One is a model where the equation itself captures the inherent nonlinearity of the data. The second is a model with time-varying coefficients. Regressions are linear when the coefficients are fixed. However, when the coefficients are allowed to vary over time, regressions can capture a great deal of nonlinearity in the data.

LIST OF ACRONYMS

WEC - Wave Energy Converter

BA - Balancing Authority

BAA - Balancing Authority Area

MW - Megawatts

GW - Gigawatts

NDBC - National Data Buoy Center