



WEC Scale Model Build & Test

Fabrication and Wave Laboratory Testing of 1/10 Scale Wave Energy Conversion Device

Prepared by
Edwin P. Mayfield Jr., Neptune Wave Power LLC
On behalf of Oregon Wave Energy Trust

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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.

Neptune Wave Power, LLC

WEC Scale Model Build & Test Summary

This official project report redacted for confidential and proprietary information in preparation for submission to Oregon Wave Energy Trust.

Prepared by:
Edwin P. Mayfield Jr.
Neptune Wave Power, LLC
4123 N. Central Expressway, Suite 1000
Dallas, Texas 75204

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Project Overview

Neptune Wave Power, LLC ('NWP'), worked with OWET, the Northwest National Marine Renewable Energy Center ('NNMREC') and Oregon State University (O.H. Hinsdale Wave Research Laboratory) to build and test a 1/10 scale model wave energy conversion ('WEC') device. This model is based upon NWP patented technology and was the latest generation design that included more sensitive instrumentation and power take-off modeling capabilities. This project included the design, build and lab test of the scale model.

The scale model was designed for multiple configurations and was run through a series of wave tests to determine the optimal configuration. Over thirty (30) configurations of the model were tested and device telemetry as well as power take-off data was collected for each series of tests.

The scale model was designed by Waldron Engineering, Inc, in Exeter, New Hampshire and built in Dallas Texas by Buzzwerks. The model and instrumentation was shipped to Oregon for the wave tests. The wave lab tests were executed at the Tsunami Wave Basin located at Oregon State University Campus. Testing goals included evaluation of buoy parameters against known wave conditions and determine the ideal buoy configuration.

The Oregon State University Tsunami Wave Basin was designed as a facility used for next generation remote tsunami research but also is used as a research facility for companies testing wave power energy converters. The tsunami basin has a length of 160 feet, width of 87 feet, a depth of 7 feet and is equipped with large stoke direction wavemaker with active wave absorption. Twenty-nine panels 6.6 feet tall can create regular, irregular, tsunami, multidirectional, or user defined wave types. Wave periods can vary from 0.5 seconds to 10 seconds.

Instrumentation used to gather data installed on the Model 2.0 buoy included a torque transducer to track pendulum position, velocity, and shaft torque and a six degrees of freedom accelerometer to determine current buoy position and track the buoy reactions to the waves. The instrumentation fed back into DSpace, a digital open source software program used to capture data. The data was then processed into a +/- 5V signal and sent to the same analog data acquisition system used by the wave gages. This system provided simple post processing of data due to time correlation.

Project Goals

The goal(s) of this project were as follows:

- Validate physical WEC design based upon NWP's patents and computer modeling
- Build 1/10 scale WEC device with additional and more sensitive instrumentation, including power take-off data gathering capabilities
- Leverage a sophisticated wave lab to run exact repeatable wave patterns against multiple device configurations
- Analyze data to refine design for 1/3 scale device targeted for ocean deployment

Model 2.0 was designed to provide the ability to make on site modifications to any of the buoy parameters listed. This allowed for different buoy configurations to be tested without the requirement to build multiple buoys.

- Buoy Floater Shape
- Pendulum Mass
- Pendulum Horizontal Position
- Pendulum Vertical Height
- Pendulum Enclosure Vertical Height
- Ballast Mass
- System Torque

To understand how the buoy configurations react with the wave period each buoy configuration was tested using an array of wave heights and wave periods. Using the data being collected a calculation to determine buoy outputs watt-second over the length of the test was created allowing on site decisions about buoy performance. This watt-second analysis calculation was verified upon reviewing data.

OWET Impact

The OWET grant allowed Neptune Wave Power, LLC to test our buoy at Oregon State University and hire and leverage the expertise that NNMREC has related to wave energy conversion device design and testing. This effort has moved our company forward and we are planning on continuing our work in Oregon, which we believe is the center of excellence in the wave energy industry in the United States.

The project was successfully executed in February and March 2011 at the O.H. Hinsdale Wave Lab working with NNMREC. The data collected has been analyzed and incorporated into the design of the next generation 1/3 scale WEC device.

Project Results

NWP has taken the results of this scale model test and implemented the optimal configuration(s) into the next generation design of their WEC device. This device will be a 1/3 scale device to be deployed in the ocean by Q4 2011. The device will include their next generation Control System to optimize the power take-off based upon varying sea states. Newport, Oregon is the likely deployment site for this ocean test, working with OWET, NNMREC and Oregon State University.

Buoy Configuration

Thirty different buoy configurations were tested over the two week testing period. Each configuration incorporated a change in one of the parameters listed in the table below. A summary table of the buoy configurations can be seen at the bottom of this and on the following page.

Buoy Floater Shape	Pendulum Mass	Pendulum Horizontal Position	Pendulum Vertical Height	Pendulum Enclosure Vertical Height	Ballast Mass	System Torque
Cylinder	6 Lbs	1 Inch to 5.5 Inch	Multiple	Multiple	None	Damper Settings
Toroid	8 Lbs	From Central	Positions Along	Positions Within	Water & Chains	Between 0.2
	10 Lbs	Shaft	Shaft	Floater	Water & Lead	and 6 Nm

Table 1: Buoy Parameter Adjustment Range

Each buoy configuration was tested against an array of wave periods and wave heights. The table below shows the testing variables done for the majority of the buoy configurations.

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Table 2: Wave Height & Period Environmental Variables

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Table 3: Buoy Configurations 1-30 Summary

A full list of all buoy configurations and the wave periods and heights tested can be seen in appendix A.

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Figure 1: Photograph of Assembled Buoy

Test Results

Upon completion of the testing, data was reviewed for correlations between the buoy configuration and wave conditions to maximize power output. Each test performed used the same exact shape of waves with differences being only in the wave height or wave period, allowing a comparison between the results of different buoy configurations. All correlations are done using the average buoy output. The peak output was also calculated and can be seen in appendix B.

As the data received from the torque transducer provided velocity, position, and torque power was calculated via the equation below and then averaged for length of the test. This power calculation assumes that all movement of the pendulum results in power generation including pendulum rocking in small increments.

$$Power_{Watts} = Torque_{Newton-Meters} \times Velocity_{radians / sec\ and}$$

Equation 1: Power Calculation

The wave state was produced using a JONSWAP, Joint North Sea Wave Observation Project, random wave spectrum. Inputs given are wave height, wave period, wave spread coefficient, and JONSWAP coefficient. Wave height and periods are sea state parameters. The wave spread coefficient is a correlation to the distribution of wave energy as a function of wave angle. The JONSWAP coefficient is used to determine the shape of individual waves. The wave spread coefficient and JONSWAP coefficient were held constant throughout the testing at 2 and 3.3 respectively. Coefficient 3.3 was chosen due to the similarity of waves off the coast of Oregon.

Wave Period

Wave period is one of the two wave conditions focused on during selection of a possible site location. To understand the relationship between the buoy and this wave condition, the different buoy model configurations were tested using a 5 inch wave height across periods of 1.0 to 1.4 seconds.

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Figure 2: Average Buoy Output – Wave Period Spectrum

Wave period, given in seconds, is a directly correlated to the wave length. The dispersion relationship for linear water waves is used to solve for the wave period, T, based on gravity, g, water depth, h, and wave length, L. (Reference: Dean and Dalrymple, Water Wave Mechanics for Engineers and Scientists, World Scientific Press)

$$\frac{T}{2\pi}^2 = g \times \frac{L}{2\pi} \times \tanh\left(\frac{L}{2\pi} \times h\right)$$

Equation 2: Wave Dispersion Relationship

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Figure 3: Wave Length / Buoy Size Relationship

Wave Height

Wave height, the second of the two wave conditions varied, was tested to understand the relationship with respect to the buoy. The buoy configurations were tested using a wave height of 4, 5, and 6 inch at a wave period of 1.1 seconds.

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Figure 4: Average Buoy Output - Wave Height Spectrum

Ballast Weight

The ballast of the buoy is a large mass located below the water line. Often used in ships to help stability, ballast for the buoy was designed to low the center of rotation of the system. Lowering the center of rotation allows the top of the buoy to move in greater increments while keeping the system stable. The affect the ballast had on the buoy was determined by testing four different ballast weight combinations. These combinations were water, water & chain, water & lead, and water & heavy lead. The remaining variables including the buoy's pendulum and environmental conditions remained constant through the testing.

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Figure 5: Average Buoy Output – Ballast Mass per Wave Height

The table below shows the mass of the total buoy, the mass of the ballast and the percentage the mass of the ballast with respect to the total buoy weight. The percentage of ballast mass to the total mass should remain similar when scaling future buoys.

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Table 4: Ballast Mass Percentage of Total Buoy Weight

Buoy Floater Shape

The shape of the buoy hull was investigated during the testing by creating two different shapes, cylinder and toroid, with the same overall dimension. These two shapes were tested under the same buoy configuration and wave parameters for comparison.

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Figure 6: Average Buoy Output – Buoy Hull Shape per Wave Height

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Figure 7: Average Buoy Output – Buoy Hull Shape per Wave Period

Pendulum Vertical Position

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Table 5: Average Power Output Difference Due to Pendulum Height

Further testing was done by lowering internal structure so that the pendulum was approximately at water level. This lowering including lowering the ballast so that the distance between the ballast and the pendulum position remained the same as the scenario with the pendulum at the top.

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Table 6: Average Power Output Difference Due to Pendulum Height

Pendulum Horizontal Position & Pendulum Mass

The pendulum position and mass are two variables of the mechanical system. The two figures below illustrate the tested horizontal position with respect to pendulum mass.

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Figure 8: Average Buoy Output - 10Lb Horizontal Pendulum Position

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Figure 9: Average Buoy Output - 6lb Horizontal Pendulum Position

Visual Observation

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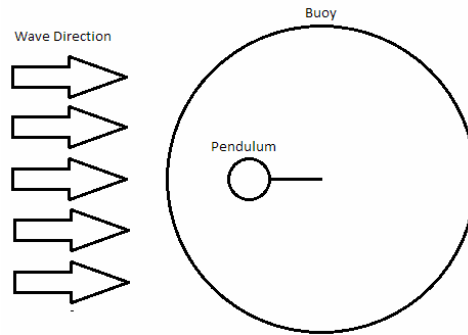


Figure 10: Pendulum / Wave Direction Alignment Illustration

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$$Energy = (\cos(\theta))^2 \times Spread$$

Equation 3: Wave Spread Relationship

Optimal Configuration

Throughout the testing one of the goals was to determine the optimal buoy configuration. Based on all testing accomplished the optimal buoy configuration can be seen in the table below in the first row. The second row represents the second choice optimal configuration. The choice of optimal buoy configuration was based on average power output exceeding the remaining buoy configurations.

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Table 7: Optimal Buoy Configuration

The average output for these two can be seen in the figure below for varying wave heights.

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Figure 11: Optimal Configuration Average Power Output

The figure below illustrates the pendulum position during the testing. This plot illustrates the rotation of the pendulum over the 320 second test period. Configuration 26 shows that numerous full rotations, 360 degrees, have occurred.

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Figure 12: Optimal Configuration Pendulum Position

Summary

Through the process of testing thirty different buoy configurations, a better understanding of the buoy parameters and wave conditions has been reached. An optimal buoy configuration was also determined and can be used as a basis for scaling to a larger size buoy.

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The risks of building a full scale model all lie within analyzing the sea state of the purposed location. If the analysis falls short on period then the result could be a significant amount of capital spent minimal power output. Before any large scale buoy is purposed, a detailed review of possible site locations should be completed.

Discussion EPRI Project

The electric power research institute has developed a formula that is used to analyze different wave energy converters. This equation uses the wave height and wave period to calculate the peak energy output per meter of buoy surface. A constant k varies from 0.3 to 0.5 and is used as a factor to determine the amount of energy within the wave. This formula can be seen below.

$$Power = k \times WaveHeight^2 \times WavePeriod$$

Equation 4: EPRI Power Calculation

This equation was used in and compared to the two best buoy configurations across the three different wave heights. The constant k was set at 0.5 and the buoy diameter of three feet the EPRI theoretical peak power output of the buoy was calculated. The figure below shows the peak output for the two different buoy configurations in comparison with the EPRI theoretical output.

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Figure 13: Peak Power Output Comparison with EPRI Project

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Discussion Orcaflex Modeling

Orcaflex modeling had been used in the past to predict the output of the buoy. Upon conclusion of the testing validation of Orcaflex could be completed using the buoy test data. This validation would allow the software to then predict the full scale reactions and output of the buoy.

Orcaflex was used to model buoy configuration 26 to validate the software. The Orcaflex inputs can be seen in Appendix C.

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Table 8: Orcaflex Outputs for Buoy Configuration 26

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Figure 14: Orcaflex Modeling Output Pendulum Position

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Figure 15: Orcaflex Modeling Output Pendulum Position

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Figure 16: Orcaflex Modeling Output Pendulum Position

Discussion Buoy Scaling

As determined above the critical variable for scaling is the wave state period. To determine the full scale buoy size sea state of the purposed location must be analyzed for both wave period and wave direction. To determine the scaling factor, the wave period between the purposed location and the model are used. The equations relating to scaling of wave conditions are shown below.

$$WaveHeight_{Model} \times ScaleRatio = WaveHeight_{Full}$$

Equation 5: Wave Height Scaling Equation

$$WavePeriod_{Model} \times \sqrt{ScaleRatio} = WavePeriod_{Full}$$

Equation 6: Wave Period Scaling Equation

After determine the correct scale factor based on the wave period, this scale factor can be used to determine the rest of the buoy parameters. The scaling factors for each parameter can be seen in the equations below. Note that this assumes the water density to be the same between the model and the full scale. If the density is different the scale ratios should be multiplied by the ratio of densities.

$$Diameter_{Model} \times ScaleRatio = Diameter_{Full}$$

Equation 7: Buoy Diameter Scaling Equation

$$Length_{Model} \times ScaleRatio = Length_{Full}$$

Equation 8: Length Scaling Equation

$$Mass_{Model} \times ScaleRatio^3 = Mass_{Full}$$

Equation 9: Mass Scaling Equation

$$Power_{Model} \times ScaleRatio^4 = Power_{Full}$$

Equation 10: Theoretical Power Scaling Equation

With these formulas it is possible to determine the overall size of the buoy and the estimated power output of the buoy.

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Scaling Procedure

To determine the size and calculate the power output of a buoy the following procedure should be followed. This process requires knowledge of the site conditions as the wave period was determined to be the critical factor.

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Scaling Example – Coast of Oregon

A scaling example was performed for a buoy off the coast of Oregon. Using NOAA buoy data (<http://www.ndbc.noaa.gov/>) hourly historical data from the 2010 year was obtained. This information included wind direction, wind speed, wind gusts speed, significant wave height, dominate wave period, average wave period, dominate wave direction, seal level pressure, air temperature, dew point temperature, station visibility, and water level above or below the mean lower low water.

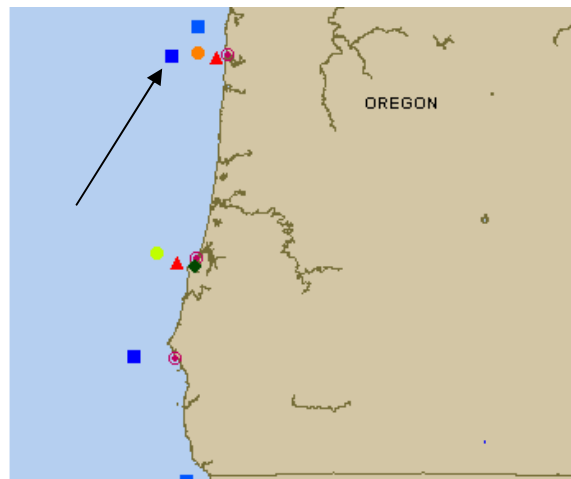


Figure 17: Oregon Cost NOAA Buoy Location

The figures below are duration curves. These curves indicate the amount of hours within the year that the wave height reaches the shown scale on the y-axis. The first plot is the wave height duration curve which shows the average wave height off the coast of Oregon is 8.6 feet but has peaked as high as 28 feet. The second curve is the wave period duration curve. This curve shows an average wave period of 7.05 seconds.

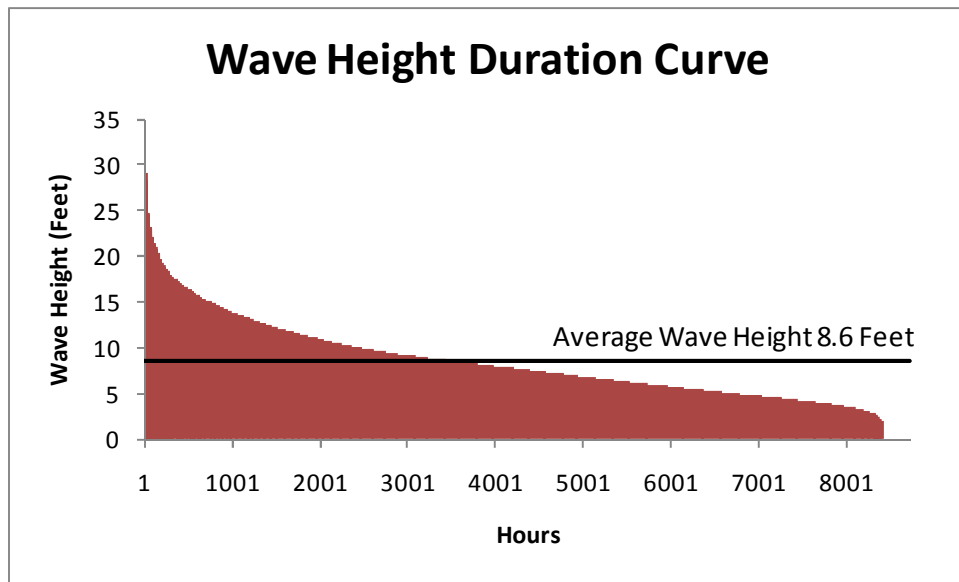


Figure 18: Oregon Coast Wave Height Duration Curve

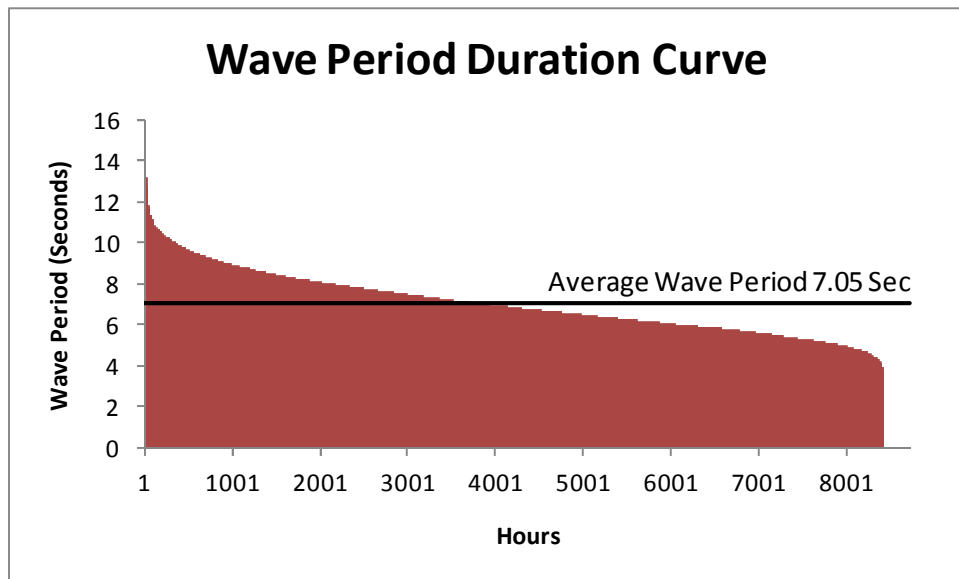


Figure 19: Oregon Coast Wave Period Duration Curve

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Table 9: Oregon Coast Full Scale Buoy Size

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Equation 11: Theoretical Power Calculation

Scaling Example – NNMREC Deployment Site

NNMREC has supplied Neptune Wave Power with the wave data for the purposed testing facility. This Data included a histogram plot of the month's wave height and wave period. These plots can be seen in Appendix D.

For each month, a weighted averaged was taken of both the wave period and wave height. This yielded an interesting trend that showed that the wave period and wave height decrease in the summer months and increase in the winter months. The table below provides the weighted averages for each month.

	Period, s	Height, ft
Janurary	10.96	11.28
Feburary	11.00	10.99
March	10.51	10.52
April	9.53	8.41
May	8.72	6.91
June	8.13	6.47
July	7.62	6.02
August	7.74	5.78
September	8.83	6.77
October	10.01	9.02
Novemeber	10.58	10.73
Decemeber	11.28	12.26

Table 10: NNMREC Deployment Site Wave Conditions

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Table 11: NNMREC Deployment Site Full Scale Buoy Size

Appendix A – Detailed Buoy Configuration

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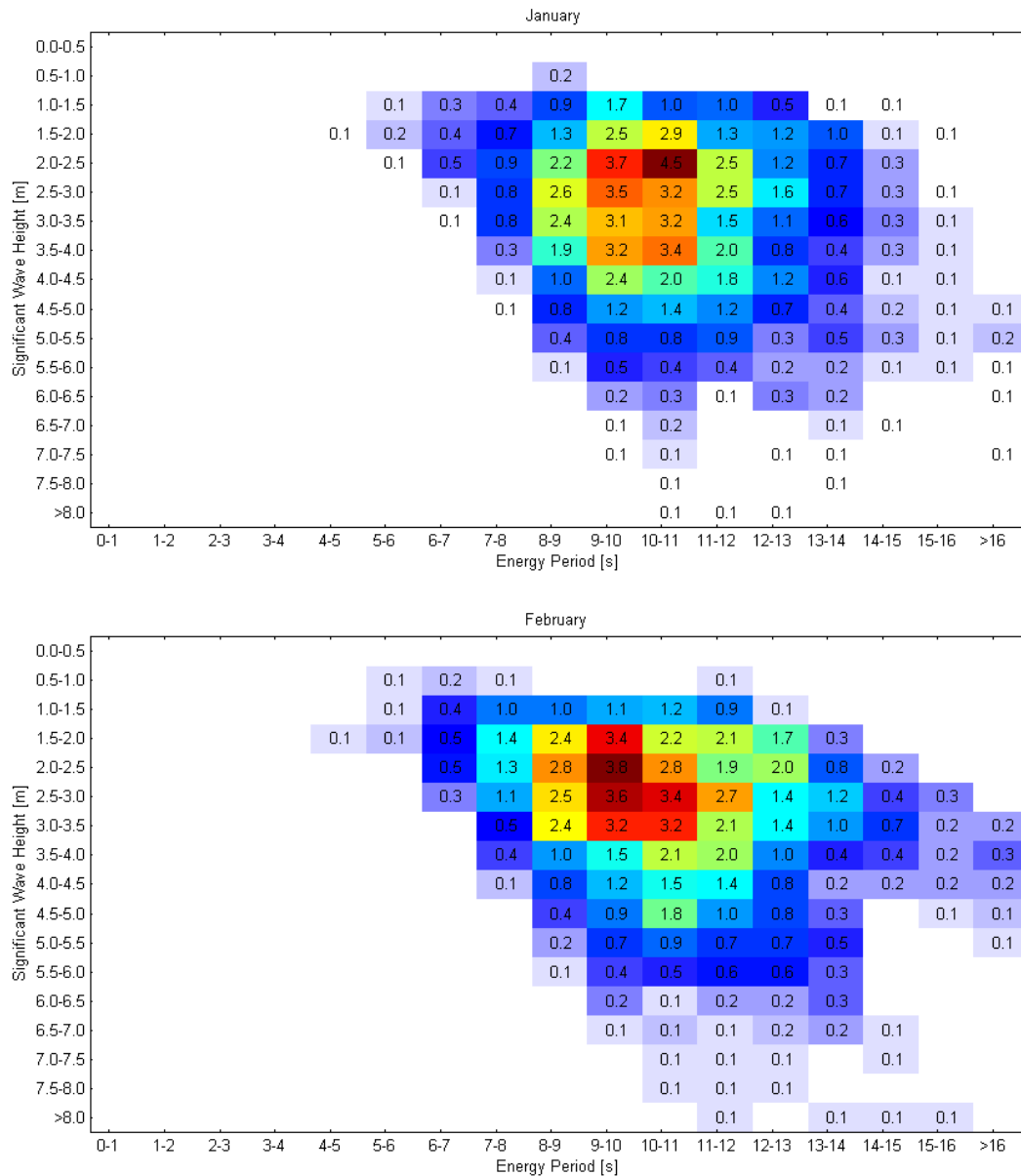
Appendix B – Power Outputs for Select Buoy Configurations

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Appendix C – Orcaflex Inputs

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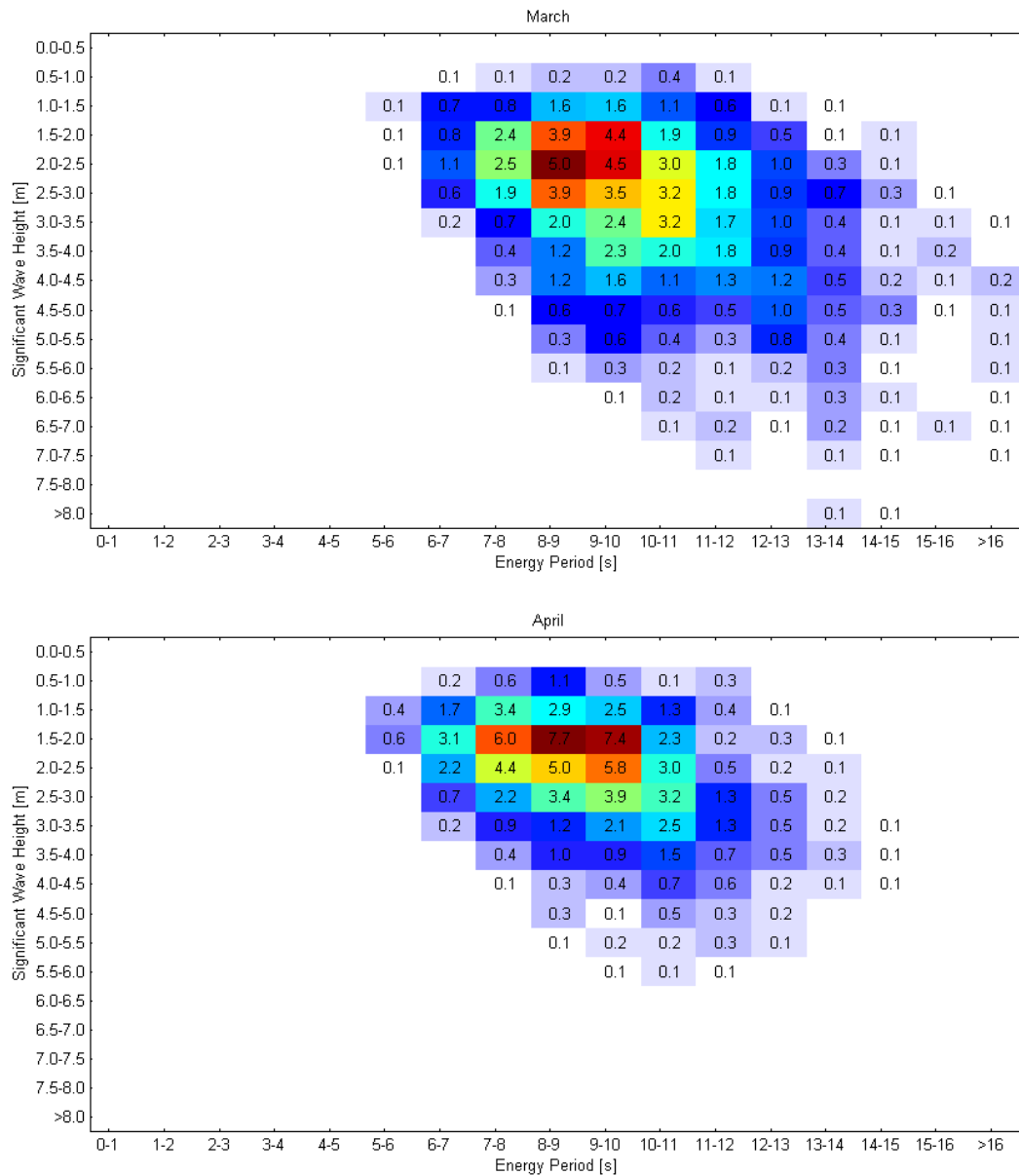
Appendix D - NNMREC Deployment Site Wave Data



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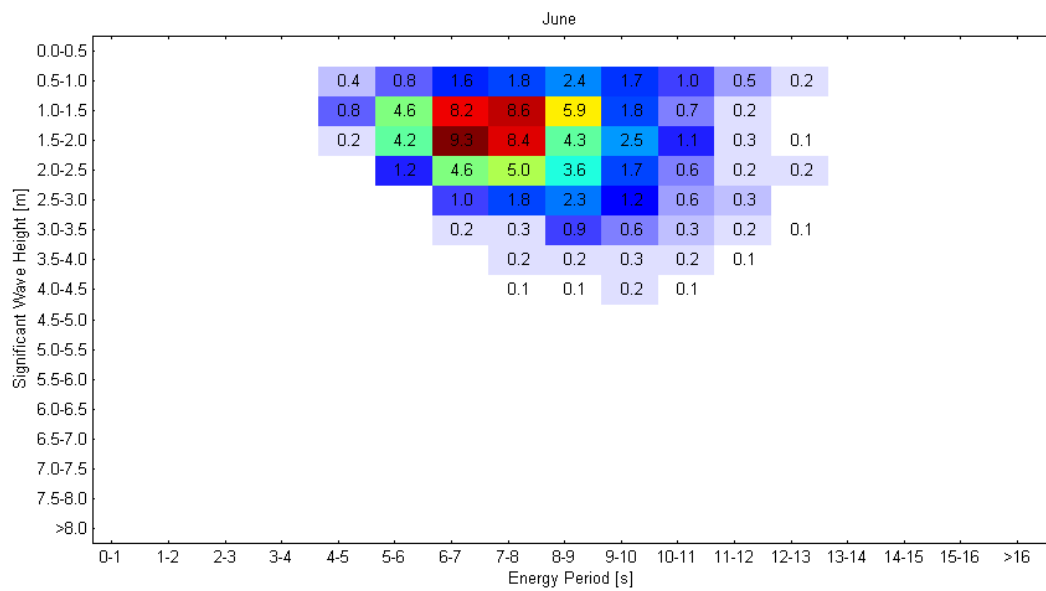
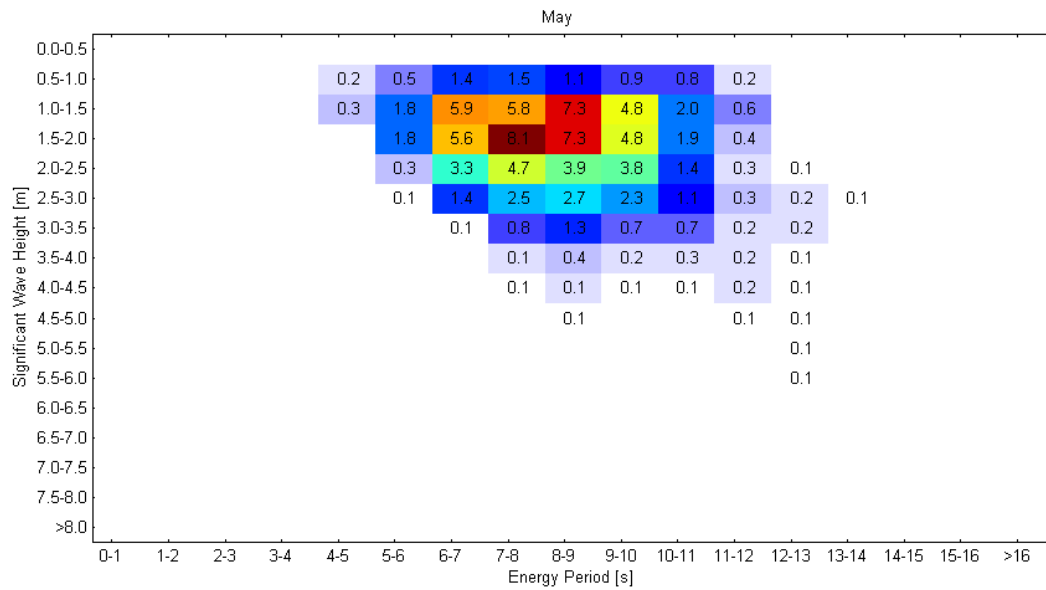
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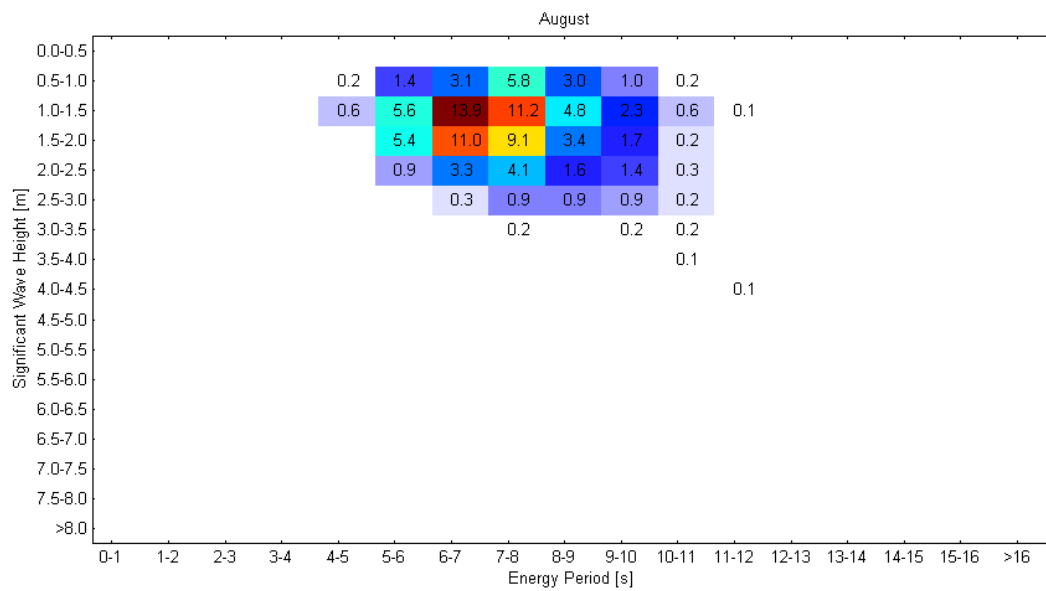
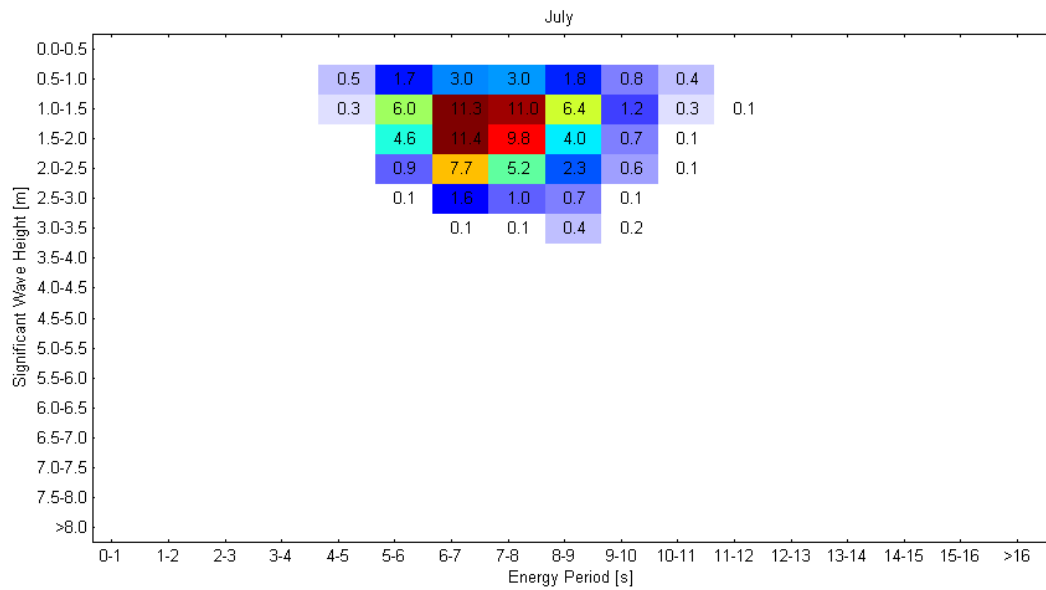
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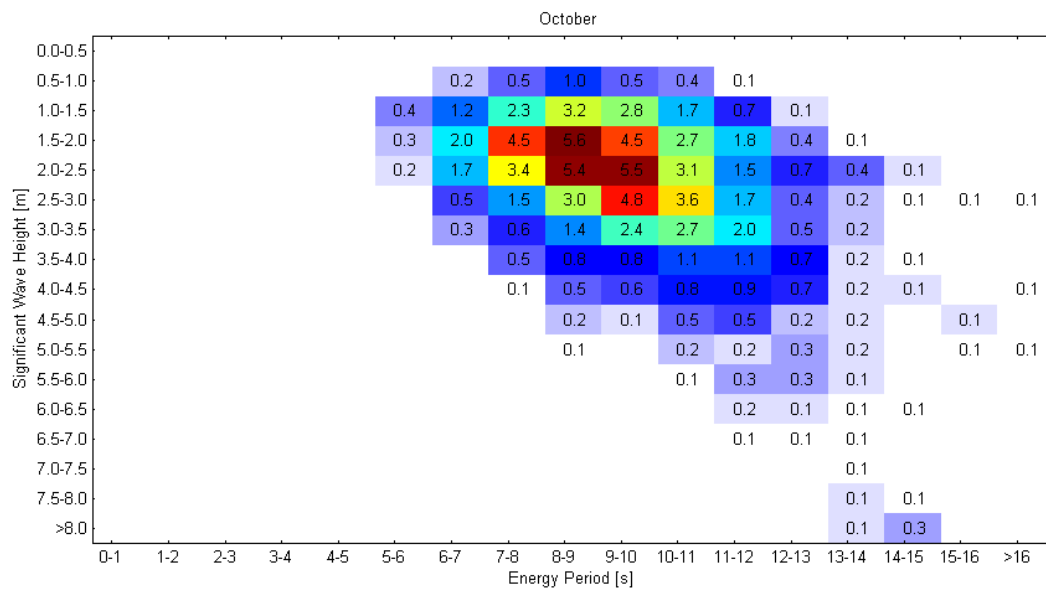
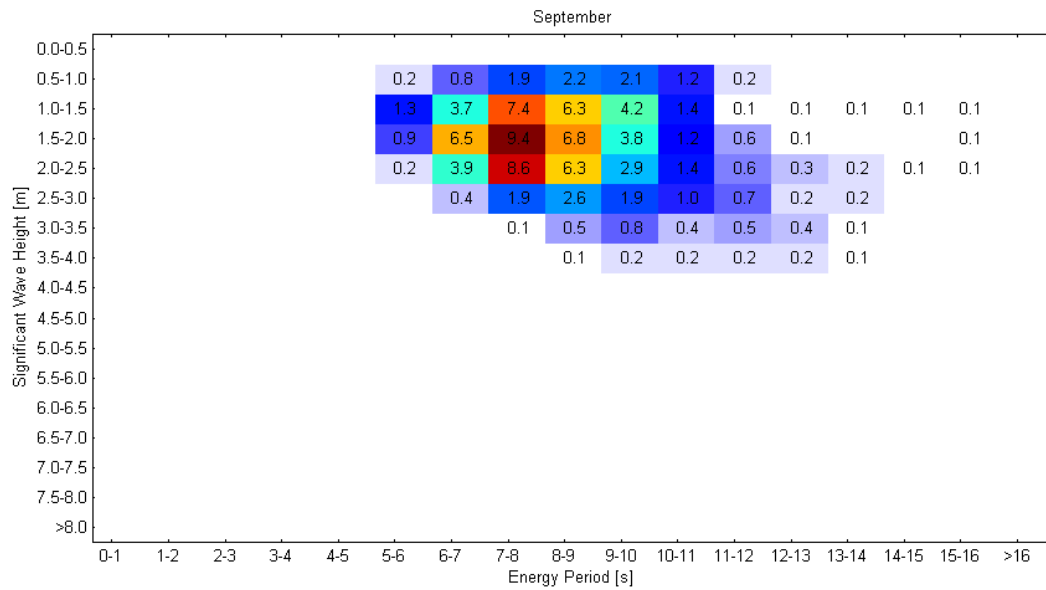
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