University of Victoria
Institute for Integrated Energy Systems

Influence of Wave Resource Assessment Methods on Wave Energy Production Estimates.

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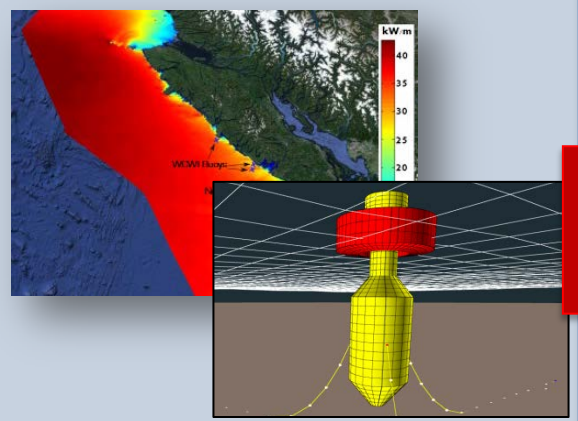
WCWI WEST COAST WAVE INITIATIVE

Motivation: Better Predictions of Annual Energy Production

Presentation Overview

Wave / WEC Database

- 10 yr SWAN Hindcast
- Amphitrite Bank Buoy



- WCWI Internal WEC
- Experimentally validated numerical model.

Assessment Method

5 Methods investigated:

- Time series zero-crossing
- IEC-TC 114 Technical Specification (JONSWAP & PM)
- Binned Representative Spectrum
- Spectrally Partitioned Spectra

Energy Production

Annual energy production for single WEC device

Required by:

- Governments
- Policy Developers
- Electrical Utilities

Wave Database

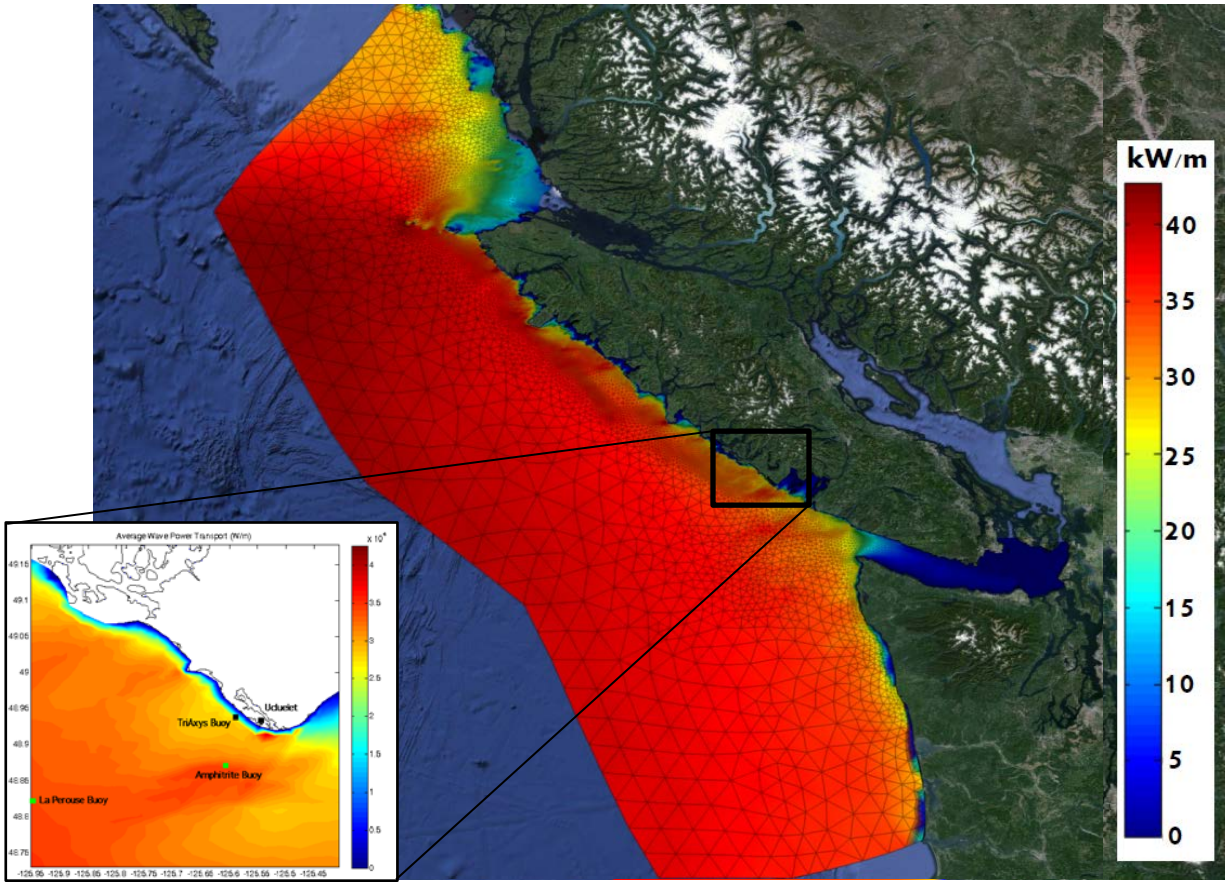
SWAN Model:

- 410 000 sq. km, 90 000 nodes, ~50m resolution
- ECMWF wave BC's and COAMPS wind BC's
- 10 yr hindcast: 0.92 & 0.80 correlation for significant wave height and average wave period respectively.

WCWI Measurement buoy:

- 48° 52.8'N, 125° 36.9'W @ 50m depth
- Deployed in 2012
- 121 frequency and 72 direction bands.
- Closest grid point < 100m.

Year: 2013



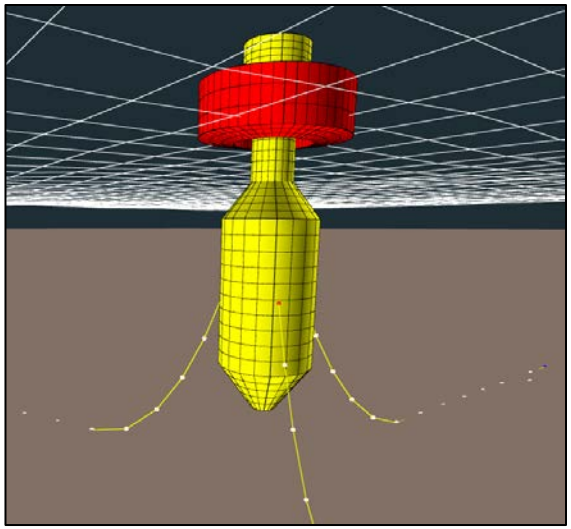
WCWI Research WEC.

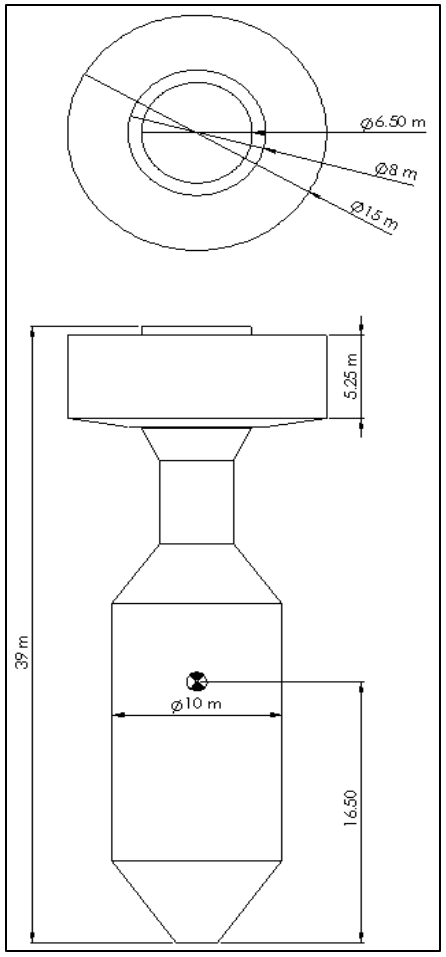
WCWI WEC:

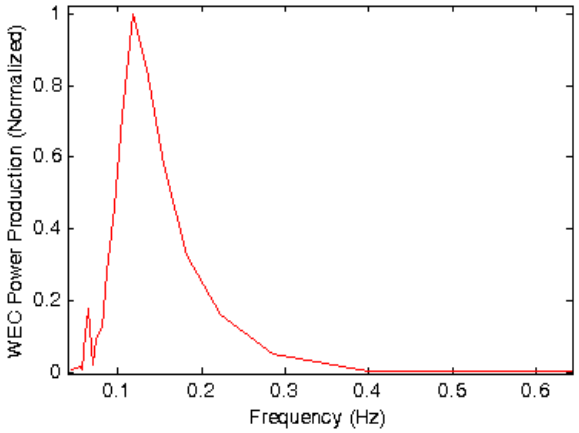
- Model based on WaveBob design.
- Internal research platform.
- 45m depth deployment.
- 3 mooring lines
- Hydraulic PTO dynamically included.
- ProteusDS performances simulations
  - 640 seconds, with initial 40 seconds removed.
- Numerical model validated against experimental tests.

Performance Curve:

- Peak power production at ~ 9 sec.
- Almost no power between 3 & 20 secs
- Normalized vertical axis



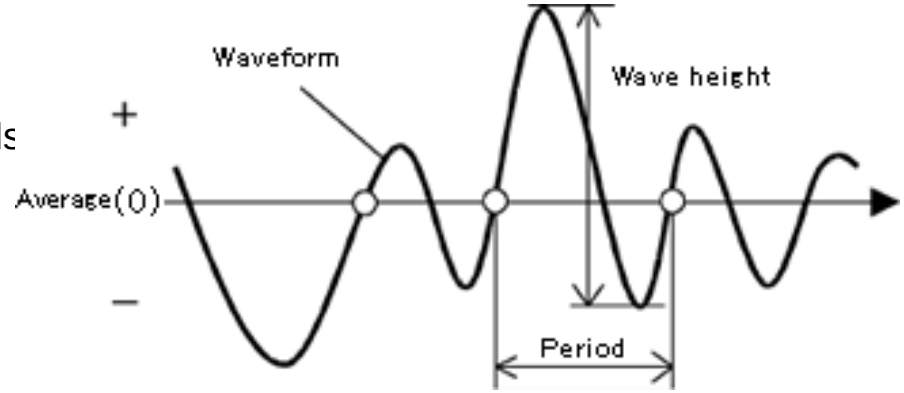




Time Series Wave Resource Asssessment

Zero-Crossing Time Series Analysis:

- Oldest method of quantifying wave heights and periods
- Wave buoy records acceleration and rate gyro information and synthesizes Heave-Northing-Easting (HNE) motions.
- Buoy HNE data at 1.75 Hz.
- Zero-up crossing method used.



Bivariate Histogram:

- Max H: 19.25 m
- Max T: 29.5 sec.
- Most Numerous: 0.25m @ 3.5 seconds.

Can only be completed for buoy. No water level time output from SWAN .

Wave Period

Wave Height

	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
2.25	8861	16650	22263	55439	27407	25004	39845	14102	10810	7968	9560	2560	1767	1806	453	253
2.75	2706	6173	9682	27742	15551	14948	24547	9300	7572	5473	7343	1878	1353	1457	311	232
3.25	785	2249	4202	13555	8197	8365	14316	5862	4477	3463	4545	1296	825	975	250	154
3.75	239	782	1803	6319	4680	4727	8414	3527	2813	2135	3088	775	585	625	218	100
4.25	32	268	828	3459	2595	2810	4994	2110	1721	1371	1849	589	400	393	100	71
4.75	4	57	257	1667	1299	1510	2970	1128	1017	860	1242	407	196	286	54	46
5.25	0	21	121	839	728	942	1749	782	546	528	725	218	161	168	57	32
5.75	0	14	36	343	450	475	917	461	318	357	471	157	154	136	18	32
6.25	0	14	7	193	246	225	621	293	232	168	307	129	82	79	18	25
6.75	0	0	7	104	96	139	389	121	154	121	175	75	57	57	14	14
7.25	0	0	4	32	57	71	186	125	75	71	171	46	25	29	11	0
7.75	0	0	0	14	32	50	125	36	54	54	89	32	43	36	0	0
8.25	0	0	0	0	7	39	64	46	36	57	50	11	18	18	4	0
8.75	0	0	0	7	4	14	54	18	25	25	25	14	11	7	0	4

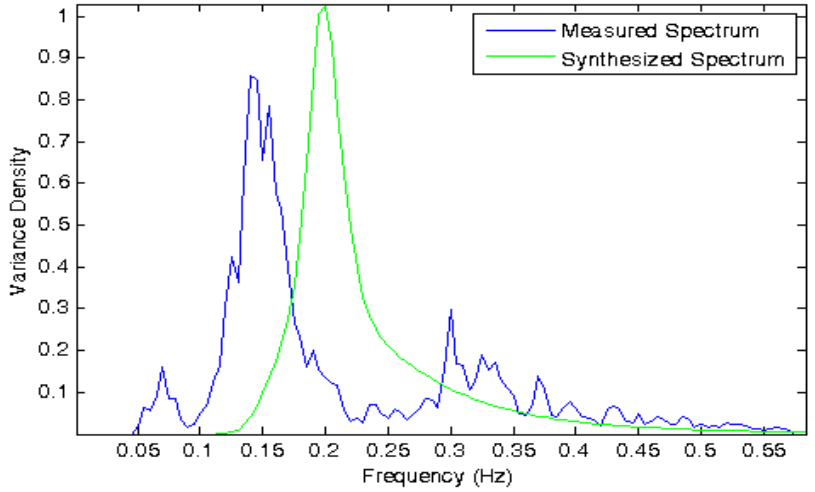
TC-114 Wave Resource Assessment Methods

TC-114 Technical Specification:

- Spectral method and allows for detailed knowledge of wave direction and individual wave system frequencies.
- Based on Significant Wave Height (Hs) and Energy Period (Te):

$$H_{m0} = 4.004\sqrt{m_0} \qquad T_e = m_{-1}/m_0$$

- Loss of information about spread of variance – hence single peaked spectrum is assumed.



SWAN Histogram:

- Max Hs: 5.75 m
- Max Te: 16.5 sec.
- Most: 1.25m @ 8.5 sec (1002)

Buoy Histogram:

- Max Hs: 7.25 m
- Max Te: 18.5 sec.
- Most: 1.25m @ 7.5 sec (682)

Wave Height (Hmo) \ Wave Energy Period (Te)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5
0.25	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.75	0	0	0	0	0	0	9	108	93	84	0	0	0	0	0	0	0
1.25	0	0	0	0	0	0	108	627	1002	810	408	102	3	0	3	0	0
1.75	0	0	0	0	0	0	18	528	618	654	366	150	39	33	3	3	0
2.25	0	0	0	0	0	0	0	90	183	384	366	246	57	18	6	24	12
2.75	0	0	0	0	0	0	0	15	66	204	219	174	117	39	3	0	0
3.25	0	0	0	0	0	0	0	0	21	105	120	114	48	30	21	0	0
3.75	0	0	0	0	0	0	0	0	9	45	45	45	48	0	0	0	0
4.25	0	0	0	0	0	0	0	0	3	21	15	27	6	0	0	0	0
4.75	0	0	0	0	0	0	0	0	0	0	3	18	3	0	0	0	0
5.25	0	0	0	0	0	0	0	0	0	0	3	3	6	0	0	0	0
5.75	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0

TC-114 Spectral Shape ?

Effect of Spectral Shape:

- TC-114 determines the distribution within the wave histogram but provides no information about spectral shape.
- Assumed: JONSWAP or Pierson-Moskowitz Spectrum.

$$E(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_{peak}}\right)^{-4}\right] \gamma^{\exp\left[-\frac{1}{2}\left(\frac{f/f_{peak}-1}{\sigma}\right)^2\right]}$$

- JONSWAP Spectrum: γ = 3.3
- PM Spectrum: γ = 1

SWAN Histogram:

- Max γ : 2.3
- Mean γ: 1.18

Buoy Histogram:

- Max γ : 7
- Mean γ : 2.03

Wave Energy Period (Te)

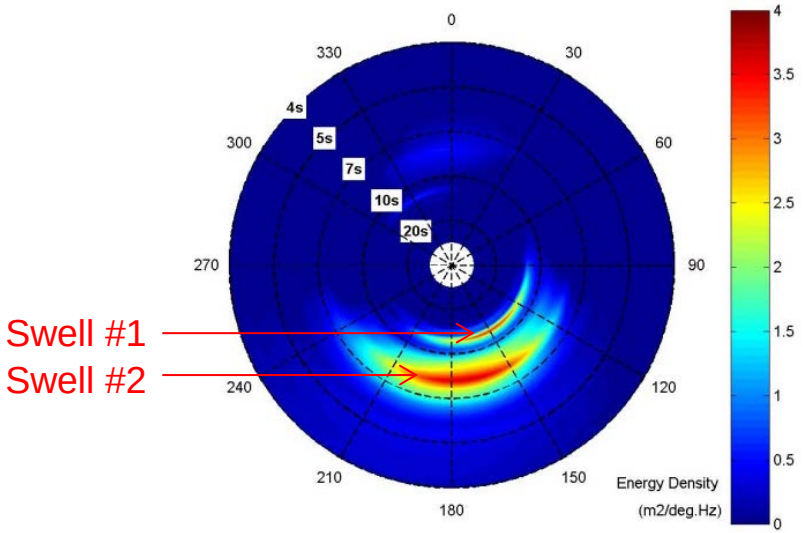
Wave Height (Hmo)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5
0.25	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.75	0	0	0	0	0	0	1.4	1	1	1	0	0	0	0	0	0	0
1.25	0	0	0	0	0	0	1	1	1	1	1	1.1	1.3	0	1.8	0	0
1.75	0	0	0	0	0	0	1	1	1	1	1	1	1.4	1.3	1.3	1.8	0
2.25	0	0	0	0	0	0	0	1	1	1	1	1	1.1	1.3	1.5	2	2.3
2.75	0	0	0	0	0	0	0	1.2	1	1	1	1	1.1	1.1	1.4	0	0
3.25	0	0	0	0	0	0	0	0	1.2	1	1	1	1.3	1.2	1.6	0	0
3.75	0	0	0	0	0	0	0	0	1	1	1	1	1.3	0	0	0	0
4.25	0	0	0	0	0	0	0	0	1.2	1	1	1.1	1.6	0	0	0	0
4.75	0	0	0	0	0	0	0	0	0	0	1	1	1.6	0	0	0	0
5.25	0	0	0	0	0	0	0	0	0	0	1	1.2	1.4	0	0	0	0
5.75	0	0	0	0	0	0	0	0	0	0	0	1.3	1.3	0	0	0	0

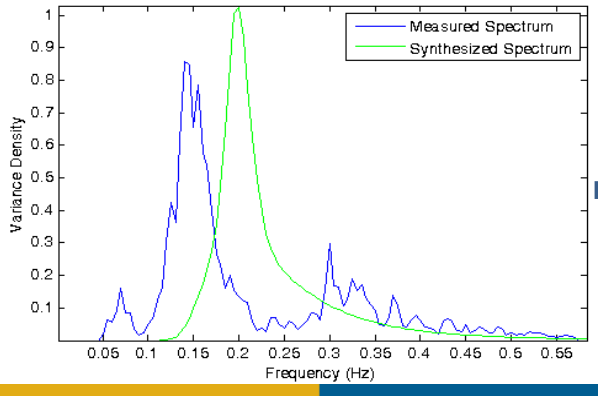
Spectral Partitioning Wave Spectra

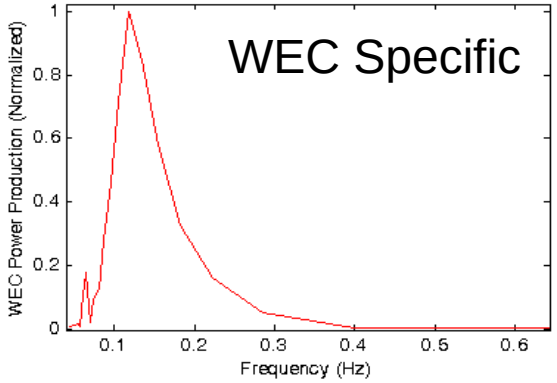
Currently, IEC Resource Assessment Technical Specification calls for use of bulk wave parameters (Hs & Te): Loss of important detail as a result lumped parameters.

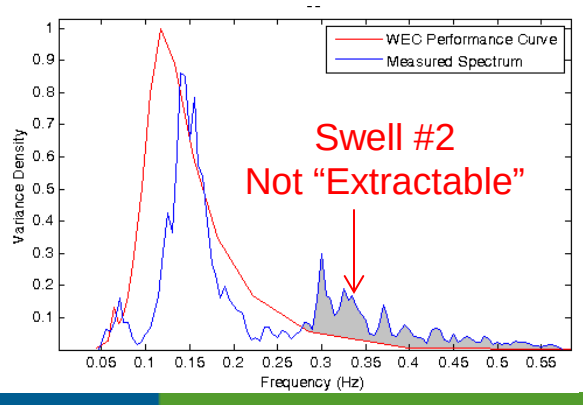
Spectral Partitioning:

- Decomposes wave spectrum into individual wave systems.
- Utilizes WEC Frequency Response to determine the "extractable" resource.
- Eliminates the inclusion of excess wave energy and inherent over prediction of gross resource.
- Shifts distribution of power in annual resource histogram.
- Based on methods from Gerling (1992)
  - Period ratio > 1.25, 20° direction, mode weights > 10.









Spectral Partitioning Wave Spectra

TC 114 – Standard Histogram

	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5
0.25	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.75	0	0	0	0	0	0	9	108	93	84	0	0	0	0	0	0	0
1.25	0	0	0	0	0	0	108	627	1002	810	408	102	3	0	3	0	0
1.75	0	0	0	0	0	0	18	528	618	654	366	150	39	33	3	3	0
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2.75	0	0	0	0	0	0	0	15	66	204	219	174	117	39	3	0	0
3.25	0	0	0	0	0	0	0	0	21	105	120	114	48	30	21	0	0
3.75	0	0	0	0	0	0	0	0	9	45	45	45	48	0	0	0	0
4.25	0	0	0	0	0	0	0	0	3	21	15	27	6	0	0	0	0
4.75	0	0	0	0	0	0	0	0	0	0	3	18	3	0	0	0	0
5.25	0	0	0	0	0	0	0	0	0	0	3	3	6	0	0	0	0
5.75	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0

TC-114 Histogram:

- Hs vs. Te
- Max Hs: 5.75 m
- Max Te: 16.5 sec.
- Most: 1.25m @ 8.5 sec (1002)

Spectrally Partitioned

Wave Energy Period

	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.75	0	0	0	0	0	0	0	94	174	171	100	26	0	0	0
1.25	0	0	0	0	0	0	48	452	1047	753	662	265	29	0	0
1.75	0	0	0	0	0	0	0	359	575	778	426	203	84	42	6
2.25	0	0	0	0	0	0	0	58	165	307	391	326	81	0	0
2.75	0	0	0	0	0	0	0	0	0	210	252	178	129	0	0
3.25	0	0	0	0	0	0	0	0	19	100	0	129	0	0	0
3.75	0	0	0	0	0	0	0	0	10	42	48	0	0	0	0
4.25	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
4.75	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0
5.25	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0

Wave Height (Hmo)

SPA Histogram:

- Hs vs. Tp
- Max Hs: 5.25 m
- Max Te: 14.5 sec.
- Most: 1.25m @ 8.5 sec (1047)

Spectral Partitioning Wave Spectra

Quick review:

- Wave climate deconstructed in numerous methods.
- Additional information about distribution of wave conditions and spectral shape.
  - eg. Pierson-Moskowitz Spectrum better representation of wave climate in BC.
- No directional effects included.
- Basic uncertainty analysis included in ICOE paper.

Interesting but…

- Large variation in predicted extracted energy (480 – 302 MWhr)
- What method provides the correct estimate ?

Method	Wave Type	Data Source	Wave Energy (MWhr)	Extracted Energy (MWhr)
Time Series	Regular Waves	Buoy	2682.56	479.87
TC-114	JONSWAP Spectrum	SWAN	2723.16	417.55
		Buoy	2613.73	434.37
TC-114	PM Spectrum	SWAN	2871.06	419.03
		Buoy	2755.05	442.96
Bin Representative	Fitted	SWAN	2867.37	430.45
		Buoy	2738.94	418.71
Spectrally Partitioned	Fitted	SWAN	2027.40	301.52
		Buoy	2029.25	326.07

Spectral Partitioning Wave Spectra

Time-Series Analysis:

- Mean energy production over 5 wave periods, only seastates with > 6 hours/year occurrence.
- Predicts 479.87 MWhr of energy annual.
- ~ 15% more than mean of all spectral methods.
  - Expected larger difference given this is a regular wave method.

Method	Wave Type	Data Source	Wave Energy (MWhr)	Extracted Energy (MWhr)
Time Series	Regular Waves	Buoy	2682.56	479.87
TC-114	JONSWAP Spectrum	SWAN	2723.16	417.55
		Buoy	2613.73	434.37
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Bin Representative	Fitted	SWAN	2867.37	430.45
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Spectrally Partitioned	Fitted	SWAN	2027.40	301.52
		Buoy	2029.25	326.07

Spectral Partitioning Wave Spectra

TC-114 Methods:

- Influence of JONSWAP vs. PM spectral shape assumption:
  - Use of PM spectrum results in larger prediction of annual wave energy (WCWI WEC)
  - However only an ~ 1% variation.
- Influence of Buoy or SWAN model data:
  - Buoy data generally results in higher energy yields (~ 5% greater)
  - Numerical models known to result in lower extreme wave conditions (see Histograms)

Bin Representative:

- Annual energy production in-line with standard TC-114 methods.
  - Expected given the previous findings on the effect of spectral shape.
  - For different WEC architectures, this result may change dramatically.

Method	Wave Type	Data Source	Wave Energy (MWhr)	Extracted Energy (MWhr)
Time Series	Regular Waves	Buoy	2682.56	479.87
TC-114	JONSWAP Spectrum	SWAN	2723.16	417.55
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Spectral Partitioning Wave Spectra

Spectral Partitioning Methods:

- Significant lower “extractable” wave power and hence lower extracted wave power.
- Eliminated unextractable power and hence providing a better estimation of extracted power.
- No longer require Te (energy period) due the elimination wave systems which are not within the performance spectrum for the WEC.
- ~ 33 % reduction for buoy data (compared to TC-114 JONSWAP method)
- ~ 39% reduction for SWAN data (compared to TC-114 JONSWAP method)

Note: The effect of spectral partitioning will vary depending on the WEC architecture or performance curve.

Method	Wave Type	Data Source	Wave Energy (MWhr)	Extracted Energy (MWhr)
Time Series	Regular Waves	Buoy	2682.56	479.87
TC-114	JONSWAP Spectrum	SWAN	2723.16	417.55
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Results and Conclusions

Known:

- Highly resolved estimates of annual wave energy production are needed.
- Numerous sources of wave data:
  - Wave buoys and numerical models.
- Numerous methods to quantify the resource:
  - Time Series Analysis, TC-114, Binned Representative, Spectrally Partitioned
  - Others in the “toolbox” yet insight from industry is required.
- WEC architecture and control methods ensure different optimum wave conditions for energy production – not included in this study.

Findings:

- Using same wave resource data, a 47% variation in energy production is estimated.
- Use of buoy data results in marginally larger estimates of energy production.
- Spectral shape:
  - PM > JONSWAP: Only marginally.
  - Representative spectrum: Indicates that SWAN results in greater energy production. Additional clarification required.
  - seems toresults in only minor changes in energy production.
- Spectrally partitioning only includes extractable wave systems and results in significantly lower energy production estimates.
  - Wave Resource Assessments must be revisited with detailed knowledge of WEC performance.

Future work…

Future Work:

- Perform systematic analysis using numerous WEC architectures.
- Identify representative double peaked spectra for each histogram bin.
- Re-think 3rd dimension in wave histogram yet strive to eliminate bulk numerical values – ensure they are physically represented.
- Analyze directional effects.
- Use spectral partitioning to identify control boundary conditions and begin to illuminate extreme/unexpected wave concerns.

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Quantifying the Wave Energy Resource and Energy Production Opportunities for British Columbia

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