Numerical Modeling Tools in Support of WEC Device Performance Evaluation at the US Navy Wave Energy Test Site (WETS)

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Numerical Modeling: How & Why

Will summarize How and concentrate in Why →

- Site specific vs. generalized WEC design
- Operational environment vs. Survival environment
- Electricity production estimates
- Premature (*unfair?*) LCOE ($/kWh)
- Considering lower Power Flux (kW/m) sites to expand market (e.g., Asia Pacific Region)

HIERARCHY OF MODELS

- Theoretical

  - Linear wave theory pioneering work (Evans, Newman, etc.): **Max. Capture Width (m) = Power Absorbed (kW)/Power Flux (kW/m)**;

  - Estimated optimal separation and ocean area requirements for OWC array

- Linear potential solvers (e.g. WAMIT)

  - Assessed published PELAMIS Power Matrix and modeled arrays to estimate ocean area requirements

  - Small amplitude wave and body motions

  - No viscous effects

  › Fast solvers

  - Single transfer function applicable to any sea state

- CFD

  - Fully nonlinear Navier-Stokes equations

  - Steep waves, Flow separation

  - Entire fluid domain discretized

  › Slow solvers

  - Each sea state (e.g., H_s, T_p) needs to be modeled

- Hybrid method

  - Hydrodynamic coefficients from ***Potential theory and CFD***

  - Much faster than CFD

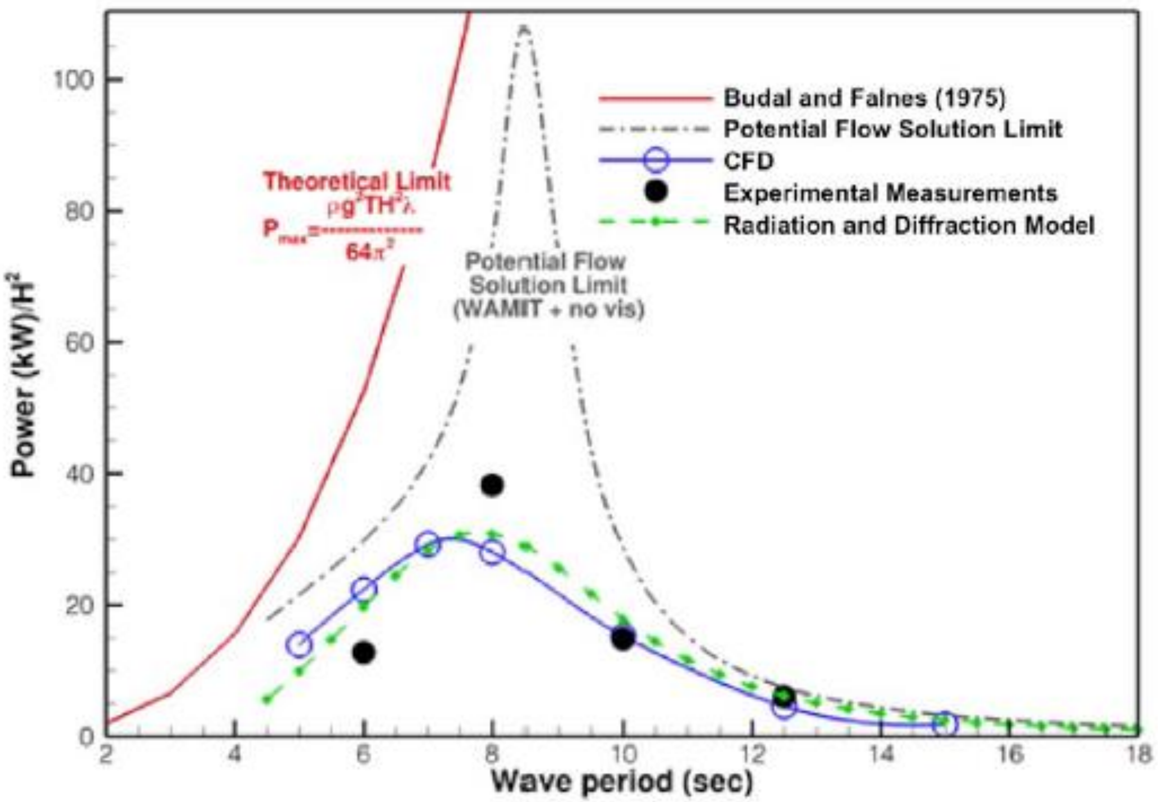
  - Each sea state also needs to be modeled

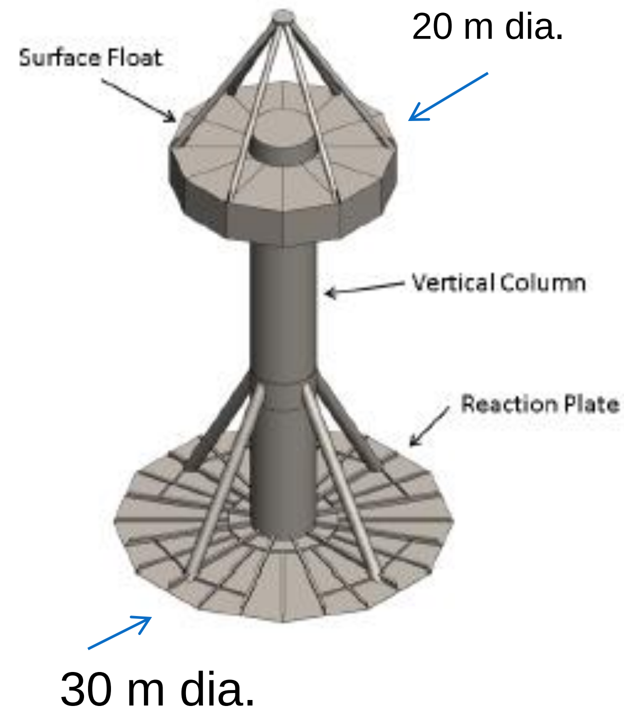
  › To be used at WETS with the AZURA and LIFESAVER

EXECUTIVE SUMMARY

- Numerical wave tank studies in agreement with experimental studies.
- Modeling WECs with FLOW-3D Solver or OpenFOAM.
- Hybrid method for operational seas.
- CFD for extreme wave conditions.
- Numerical models will be used to assess performance of WEC devices to be tested at WETS (*MOA required*)

Mirko's Illustration of Models Available





(2.5 m regular wave from Mirko Previsic et al)

- Hybrid method compares well with CFD, Experiments
- Extreme wave scenarios ***<u>only with</u>*** CFD, Experiments

Wave Resource

Challenge: Site specific wave power flux Po (kW/m) vary significantly over the year with summer months at ~ 10% of the winter values

WETS: Annual Average:12 kW/m; Peak Hourly:170 kW/m

Te, Energy Period

Hs

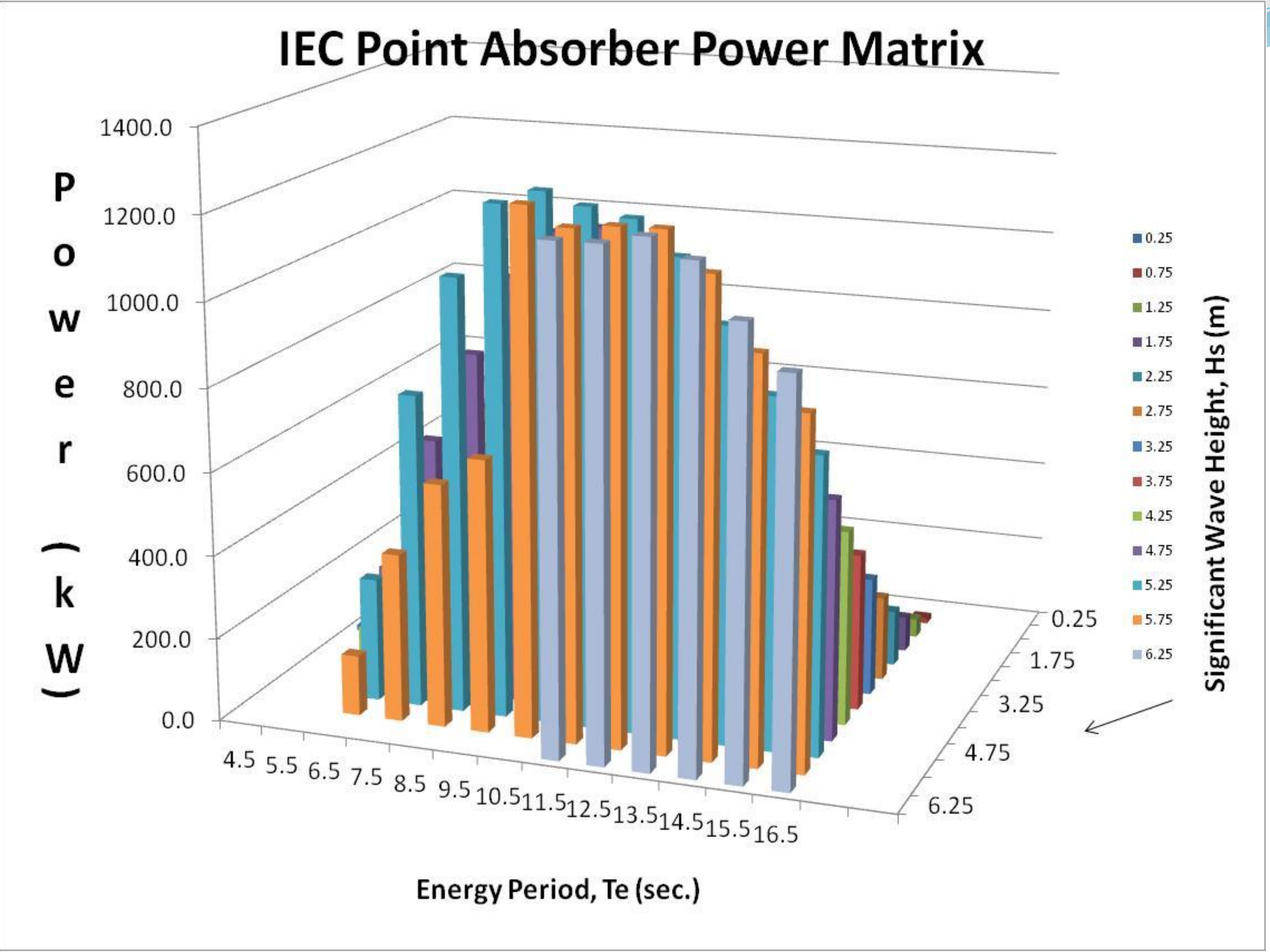
	4.5 s	5.5 s	6.5 s	7.5 s	8.5 s	9.5 s	10.5 s	11.5 s	12.5 s	13.5 s	14.5 s
0.75 m											
1.25 m											
1.75 m											
2.25 m											
2.75 m											
3.25 m											
3.75 m											
4.25 m											
4.75 m											
5.25 m											
5.75 m											
6.25 m											
6.75 m											
7.25 m											
7.75 m											

Power Flux Distribution Po (kW/m) 90% Cumulative

	4.5 s	5.5 s	6.5 s	7.5 s	8.5 s	9.5 s	10.5 s	11.5 s	12.5 s	13.5 s	14.5 s
0.75 m											
1.25 m											
1.75 m											
2.25 m											
2.75 m											
3.25 m											
3.75 m											
4.25 m											
4.75 m											
5.25 m											
5.75 m											
6.25 m											
6.75 m		Pauwela (Annual Average: 23 kW/m; Peak Hourly: 350 kW/h)									
7.25 m		Distribution Po (kW/m) 90% Cumulative									
7.75 m											

	4.5 s	5.5 s	6.5 s	7.5 s	8.5 s	9.5 s	10.5 s	11.5 s	12.5 s	13.5 s	14.5 s
0.75 m											
1.25 m											
1.75 m											
2.25 m											
2.75 m											
3.25 m											
3.75 m											
4.25 m											
4.75 m											
5.25 m											
5.75 m											
6.25 m	Grays Harbor (Annual Average: 31 kW/m; Peak Hourly: 1160 kW/m)										
6.75 m											
7.25 m											
7.75 m											

WEC Device Power Matrix



IEC Point Absorber Power Matrix
Power (kW)
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
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
Energy Period, Te (sec.)
0.25
1.75
3.25
4.75
6.25
Significant Wave Height, Hs (m)
0.25
0.75
1.25
1.75
2.25
2.75
3.25
3.75
4.25
4.75
5.25
5.75
6.25

IEC Name Plate: "1 MW"

	4.5 s	5.5 s	6.5 s	7.5 s	8.5 s	9.5 s	10.5 s	11.5 s	12.5 s	13.5 s	14.5 s
0.75 m											
1.25 m			IEC Sample Power Matrix (showing bins > 20% name plate)								
1.75 m											
2.25 m						0.23	0.27	0.28	0.26	0.22	
2.75 m				0.20	0.28	0.34	0.39	0.42	0.39	0.32	0.27
3.25 m				0.29	0.40	0.48	0.55	0.58	0.54	0.45	0.38
3.75 m			0.22	0.38	0.54	0.64	0.73	0.77	0.72	0.59	0.49
4.25 m			0.27	0.48	0.68	0.82	0.93	0.97	0.91	0.75	0.63
4.75 m			0.29	0.62	0.84	1.03	1.14	1.16	1.10	0.97	0.82
5.25 m			0.30	0.76	1.04	1.22	1.26	1.23	1.21	1.13	0.98
5.75 m				0.40	0.58	0.65	1.25	1.20	1.21	1.21	1.12
6.25 m								1.19	1.20	1.22	1.18
6.75 m										1.16	1.12
7.25 m											
7.75 m											

	4.5 s	5.5 s	6.5 s	7.5 s	8.5 s	9.5 s	10.5 s	11.5 s	12.5 s	13.5 s	14.5 s
0.75 m											
1.25 m											
1.75 m											
2.25 m			0.23	0.26	0.25	0.22					
2.75 m		0.22	0.34	0.39	0.36	0.31	0.25	0.21			
3.25 m		0.31	0.48	0.52	0.48	0.42	0.34	0.28	0.23	0.21	
3.75 m		0.36	0.61	0.66	0.60	0.53	0.44	0.35	0.29	0.26	
4.25 m			0.76	0.80	0.73	0.64	0.53	0.44	0.36	0.32	
4.75 m			0.92	0.92	0.85	0.76	0.64	0.52	0.43	0.40	
5.25 m			0.99	0.99	0.96	0.85	0.74	0.61	0.50	0.46	
5.75 m			1.00	1.00	1.00	0.94	0.81	0.70	0.58	0.51	
6.25 m				1.00	1.00	1.00	0.92	0.79	0.65	0.60	
6.75 m				1.00	1.00	1.00	1.00	0.86	0.73	0.67	
7.25 m				1.00	1.00	1.00	1.00	0.95	0.80	0.75	
7.75 m					1.00	1.00	1.00	1.00	0.87	0.81	

Pelamis: 750 kW
150 m/ 3.5 m dia/ 3 hinges
100 MW Farm: 4 km^2

	4.5 s	5.5 s	6.5 s	7.5 s	8.5 s	9.5 s	10.5 s	11.5 s	12.5 s	13.5 s	14.5 s
0.75 m											
1.25 m			IEC Sample Power Matrix (showing bins > 20% name plate)								
1.75 m											
2.25 m						0.23	0.27	0.28	0.26	0.22	
2.75 m				0.20	0.28	0.34	0.39	0.42	0.39	0.32	0.27
3.25 m				0.29	0.40	0.48	0.55	0.58	0.54	0.45	0.38
3.75 m			0.22	0.38	0.54	0.64	0.73	0.77	0.72	0.59	0.49
4.25 m			0.27	0.48	0.68	0.82	0.93	0.97	0.91	0.75	0.63
4.75 m			0.29	0.62	0.84	1.03	1.14	1.16	1.10	0.97	0.82
5.25 m			0.30	0.76	1.04	1.22	1.26	1.23	1.21	1.13	0.98
5.75 m				0.40	0.58	0.65	1.25	1.20	1.21	1.21	1.12
6.25 m								1.19	1.20	1.22	1.18
6.75 m										1.16	1.12
7.25 m											
7.75 m											

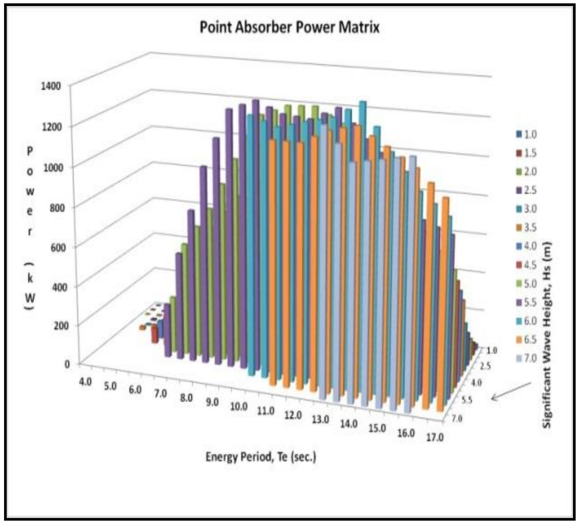
IEC Name Plate: "1 MW"

	4.5 s	5.5 s	6.5 s	7.5 s	8.5 s	9.5 s	10.5 s	11.5 s	12.5 s	13.5 s	14.5 s
0.75 m											
1.25 m	0.23	0.32	0.34	0.33	0.32	0.30	0.28	0.26	0.24	0.22	
1.75 m	0.44	0.58	0.58	0.56	0.51	0.49	0.44	0.41	0.37	0.35	
2.25 m	0.72	0.87	0.83	0.80	0.72	0.69	0.62	0.56	0.52	0.48	
2.75 m	1.00	1.00	1.00	1.00	0.95	0.90	0.81	0.74	0.67	0.61	
3.25 m	Storm	Protection	→								
3.75 m											
4.25 m											
4.75 m				Wave Star C5 (20 floats) Power Matrix: Bins > 20% Name Plate							
5.25 m											
5.75 m											
6.25 m											
6.75 m											
7.25 m											
7.75 m											

Non-Resonant Point Absorber (Tn: 4.5 s)
Wave Star C5: 600 kW
20 x 5 m dia. floats

WEC Device Performance:

Electrical output vs. wave parameters



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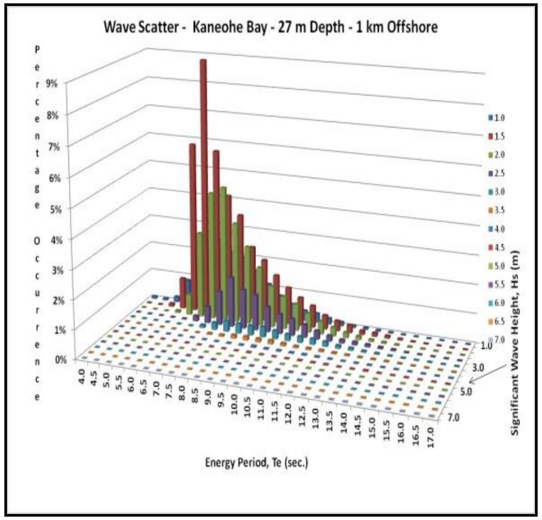

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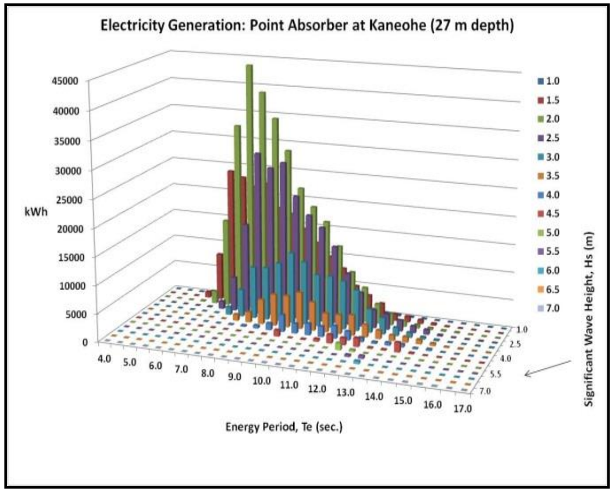


Power Matrix:
kW vs. Hs/Te

Wave Scatter:
Occurrence vs. Hs/Te

kWh vs. Hs/Te

Electrical Generation with Hypothetical (IEC) "1 MW" Point Absorber

Site	Wave Scatter	Annual Po (kW/m)	Annual MWh	Max hour Po (kW/m)
Pauwela (Maui) 73 m Depth	Hindcast (1990-2009) 3 km offshore	23	1,540 CF: 0.18	350
Grays Harbor (WN) 40 m Depth	NDBC (1987-2008) 9 km offshore	31	1,968 CF: 0.23	1160
Col. Rvr Bar (WN/OR) 135 m Depth	NDBC (1999-2008) 40 km offshore	40	2,546 CF: 0.29	1420
		Theoretical Resource	**Technical Resource**	**Survival**

Can your WEC device survive 1300 kW/m?

Premature/Simplistic WEC Economics

- CF ≡ production (kWh)/ [8760 hrs x name plate (kW)]
- WEC CFs similar to

PV Arrays (~ 0.16 - 0.2); Wind Farms (~ 0.2 - 0.5)

- 100 MW Array requires:

  ~ 2 km^2 (PV); < 7 km^2 (WEC); < 12 km^2 (Offshore Wind)

- <u>CC target</u> for WECs vs. Wind Farms (~ 2,000 $/kW); and PV Arrays (~ 6,000 $/kW)
- WEC CC estimates: range from 30,000 $/kW (prototypes) to target of 3,000 $/kW (commercialization in ~ 10 years?)

Case	Size	Cap. Fac.	CC	Loan (I/N)	*COE cc*	*COE omrr*	COE
			($/kW)	%/years	*$/kWh*	*$/kWh*	$/kWh
Future	*90 MW*	0.40	3,000	8/15	*0.1*	*0.070*	**0.17**
"		"	"	2.5/20	*0.055*	*0.077*	**0.13**
Future	*90 MW*	0.25	3,000	8/15	*0.16*	*0.112*	**0.27**
"		"	"	2.5/20	*0.088*	*0.123*	**0.21**
Future	*90 MW*	0.15	3,000	8/15	*0.267*	*0.187*	**0.45**
"		"	"	2.5/20	*0.147*	*0.206*	**0.35**
1st Gen.	750 kW	0.40	10,000	8/15	*0.333*	*0.233*	**0.57**
		"	"	2.5/20	*0.183*	*0.257*	**0.44**
1st Gen.	750 kW	0.25	10,000	8/15	*0.534*	*0.372*	**0.91**
		"	"	2.5/20	*0.293*	*0.411*	**0.70**
1st Gen.	750 kW	0.15	10,000	8/15	*0.891*	*0.623*	**1.51**
		"	"	2.5/20	*0.489*	*0.687*	**1.18**

Premature/Unfair LCOE ($/kWh) estimates

Asia Pacific Region: Offshore Wave Power Flux (kW/m)

Nation	Ref. 2 (Cornett)	Ref. 3 (Fugro OCEANOR)	Wave Resource > 10kW/m
CENTRAL and WEST ASIA			
Pakistan	< 10 kW/m	5 to 10 kW/m	No
EAST ASIA			
People's Republic of China	< 10 kW/m	5 to 10 kW/m	No
PACIFIC			
Reference Site (Hawaii Global)	*North: 30 to 40 kW/m* *South: 20 to 30 kW/m*	*North: 30 to 40 kW/m* *South: 20 to 30 kW/m*	*Yes*
Cook Is./Rarotonga (~ 160 °W/22 °S)	30 to 40 kW/m	~ 20 to 30 kW/m	Yes
Fiji Islands (~ 178 °E/17 °S)	10 to 20 kW/m	< 20 kW/m	Yes
Kiribati/Tarawa (~ 175 °E/2 °N)	< 10 kW/m	5 to 10 kW/m	No
Marshall Islands/Majuro (~ 170 °E/5 °N)	10 to 20 kW/m	10 to 15 kW/m	Yes
Federated States of Micronesia (Global)	10 to 20 kW/m	10 to 15 kW/m	Yes
Nauru (~ 165 °E/0 °)	10 to 20 kW/m	10 to 15 kW/m	Yes
Palau (~ 135 °E/5 °N)	< 10 kW/m	10 to 15 kW/m	No
Papua New Guinea (Global)	< 10 kW/m	5 to 10 kW/m	No
Samoa (~ 172 °W/12 °S)	10 to 20 kW/m	10 to 15 kW/m	Yes
Solomon Islands (~ 160 °E/10 °S)	< 10 kW/m	10 to 15 kW/m	No
Timor-Leste (Global)	< 10 kW/m	5 to 10 kW/m	No
Tonga (~ 175 °W/22 °S)	10 to 20 kW/m	15 to 20 kW/m	Yes
Tuvalu (~ 180 ° /5 to 10 °S)	10 to 20 kW/m	15 to 20 kW/m	Yes
Vanuatu (~ 165 °E/15 °S)	10 to 20 kW/m	10 to 15 kW/m	Yes
SOUTH ASIA			
Bangladesh	< 10 kW/m	10 to 15 kW/m	No
India	- South Coast off Nadu: 10 to 20 kW/m - Elsewhere < 10 kW/m	Arabian Sea: 15 to 20 kW/m West & South Coasts: 10 to 15 kW/m	Yes
Maldives	10 to 20 kW/m	10 to 15 kW/m	Yes
Sri Lanka	- South Coast off Matara: 10 to 20 kW/m - Elsewhere < 10 kW/m	15 to 20 kW/m	Yes
SOUTHEAST ASIA			
Brunei Darussalam	< 10 kW/m	< 5 kW/m	No
Cambodia	< 10 kW/m	5 to 10 kW/m	No
Indonesia	- South Java: 20 to 30 kW/m - Elsewhere < 10 kW/m	South Java: 20 to 30 kW/m	Yes
Malaysia	< 10 kW/m	< 5 kW/m	No
Myanmar	< 10 kW/m	5 to 10 kW/m	No
Philippines	- North (Luzon & Babyan Is.): 10 to 20 kW/m - Elsewhere < 10 kW/m	- North: 15 to 20 kW/m - Elsewhere < 5 kW/m	Yes
Thailand	< 10 kW/m	< 5 kW/m	No
Viet Nam	< 10 kW/m	< 5 kW/m	No

To be Continued….

Annex: Q&A

Hybrid approach for generating power matrix

Differential equation of heave motion

Mass

$$(M + \mu_{\infty})\ddot{Z} = F_{ex} - \int_0^t K(t-\tau)\dot{Z}(\tau)dt + \ldots$$

Heave added mass (e.g. from WAMIT)

Excitation force (from Spectrum & say WAMIT)

Memory function for radiation forces (e.g. from WAMIT)

$$\ldots + F_H + F_{PTO} + F_V \qquad \text{Eq. (1)}$$

Hydrostatic force (from wetted surface area)

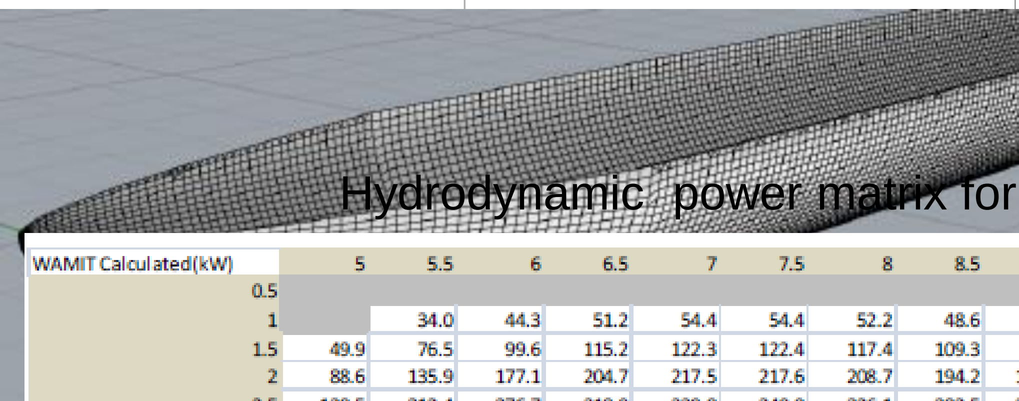
from Power Take Off load (PTO load)

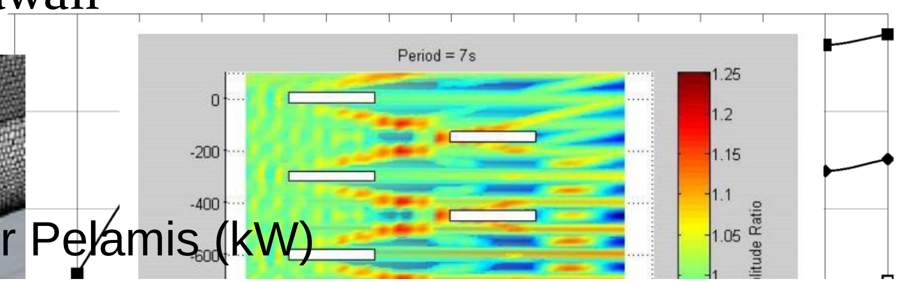
Viscous damping force from CFD (e.g. OpenFOAM)

WAMIT
Theoretical

Frederick, M., 2014. Hydrodynamic Modeling of Pelamis® P1-750 Wave Energy Converters using WAMIT software. Master of Science Plan B Research Paper, ORE, University of Hawaii

Nihous, G.C., 2012. Wave power extraction by arbitrary arrays of non-diffracting oscillating water columns. Ocean Engineering 51, 94-105.





Hydrodynamic power matrix for Pelamis (kW)

WAMIT Calculated(kW)	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13	T_e
0.5																		
1		34.0	44.3	51.2	54.4	54.4	52.2	48.6	44.3	39.8	35.3	31.2	27.5	24.1				
1.5	49.9	76.5	99.6	115.2	122.3	122.4	117.4	109.3	99.6	89.4	79.5	70.3	61.8	54.3	47.6	41.8	36.7	750(kW) Max
2	88.6	135.9	177.1	204.7	217.5	217.6	208.7	194.2	177.0	159.0	141.4	124.9	109.9	96.5	84.6	74.2	65.2	
2.5	138.5	212.4	276.7	319.9	339.8	340.0	326.1	303.5	276.6	248.4	220.9	195.2	171.7	150.7	132.2	116.0	101.9	
3	199.4	305.8	398.4	460.7	489.4	489.6	469.5	437.0	398.3	357.8	318.1	281.0	247.3	217.1	190.4	167.0	146.7	
3.5		416.3	542.2	627.0	666.1	666.4	639.1	594.8	542.1	486.9	433.0	382.5	336.5	295.4	259.1	227.4	199.7	
4			708.2	819.0	870.0	870.4	834.7	776.9	708.1	636.0	565.6	499.6	439.6	385.9	338.5	297.0	260.8	
4.5			896.4	1036.5	1101.1	1101.6	1056.4	983.3	896.2	804.9	715.8	632.3	556.3	488.4	428.4	375.8	330.1	
5				1279.6	1359.4	1360.0	1304.2	1213.9	1106.4	993.8	883.7	780.6	686.8	602.9	528.9	464.0	407.5	
5.5				1548.4	1644.8	1645.6	1578.1	1468.9	1338.8	1202.5	1069.3	944.6	831.0	729.5	639.9	561.4	493.0	
6					1957.5	1958.4	1878.1	1748.1	1593.2	1431.0	1272.5	1124.1	989.0	868.2	761.6	668.1	586.8	
6.5					2297.3	2298.4	2204.1	2051.5	1869.8	1679.5	1493.4	1319.3	1160.7	1018.9	893.8	784.1	688.6	
7						2665.6	2556.3	2379.3	2168.6	1947.8	1732.0	1530.1	1346.1	1181.7	1036.6	909.4	798.6	
7.5							2934.5	2731.3	2489.4	2236.0	1988.3	1756.5	1545.3	1356.6	1189.9	1044.0	916.8	
8								3107.7	2832.4	2544.0	2262.3	1998.5	1758.2	1543.5	1353.9	1187.8	1043.1	
H_s																		

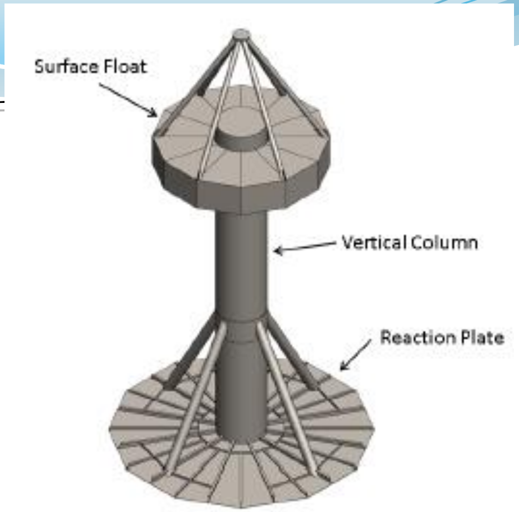
Nihous, G.C., “Maximum wave power absorption by flexible line attenuators,” *Applied Ocean Research*, **43**, 68-70, 2013.

Nihous, G.C., “Maximum wave power absorption by slender bodies of arbitrary cross sections in oblique seas,” *Applied Ocean Research*, **47**, 17-27, 2014.

Development of a Numerical Wave Tank

- Goal: to allow computer simulations of wave energy converters (WECs) at laboratory and model basin scales
- This would enable the validation of WEC designs without extensive and costly experiments
- Methodology to date : use and modify an open source Computational Fluid Dynamics (CFD) solver (OpenFOAM)

Progress



- Experiments with flat plates (2D & 3D)
- Validation of the model started with a 2D simulation of Keulegan & Carpenter's seminal experiments (1958)
- The next step involved the modeling of 3D moving objects with prescribed motions, for which data sets have been published
- These cases are highly nonlinear, and relevant in realistic designs (e.g., heave plates)