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Scaling Down a Wave Energy Converter to Match the Wave Spectrum of the North Carolina Coast

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North Carolina Renewable Ocean Energy Program

Coastal Studies Institute
A Multi-Institutional Research Partnership

Our Team

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Objectives

- Perform an assessment of North Carolina’s wave parameters and energy resource and determine optimal site locations
- **Adapt and optimize a Wave Energy Converter** (WEC) design for North Carolina’s wave resource characteristics
- Identify opportunities for **improving energy density** and **levelized cost of energy (LCOE)** [$/kWh]

Wave Resource Assessment

Data Source:
- WaveWatch III Data from July 2005-December 2018
- HYCOM Data (for wave depths)

Wave Parameters of Interest:
- Wave Height
- Wave Period
- Water Depth
- Energy Flux (derived from wave height and wave period)

Process:
- 491 site locations
- Water depth < 200m
- Data segmented into 3 hours
- Analyzed statistical information

Outputs:
- Joint Probability Distribution Matrix (Sea States)
- Seasonality impact on Wave Height & Periods
- Energy Flux Density for the site locations

Joint Probability Distribution

- **Sea State Frequency Map:**
  - **Captures how often each sea state occurs** (Hs × Te), forming the statistical basis for WEC design
- **Design Optimization Input:**
  - Guides selection of rated capacity and operating range to maximize energy capture in real conditions
- **Consistent Performance Modeling:**
  - Ensures simulations reflect actual wave conditions

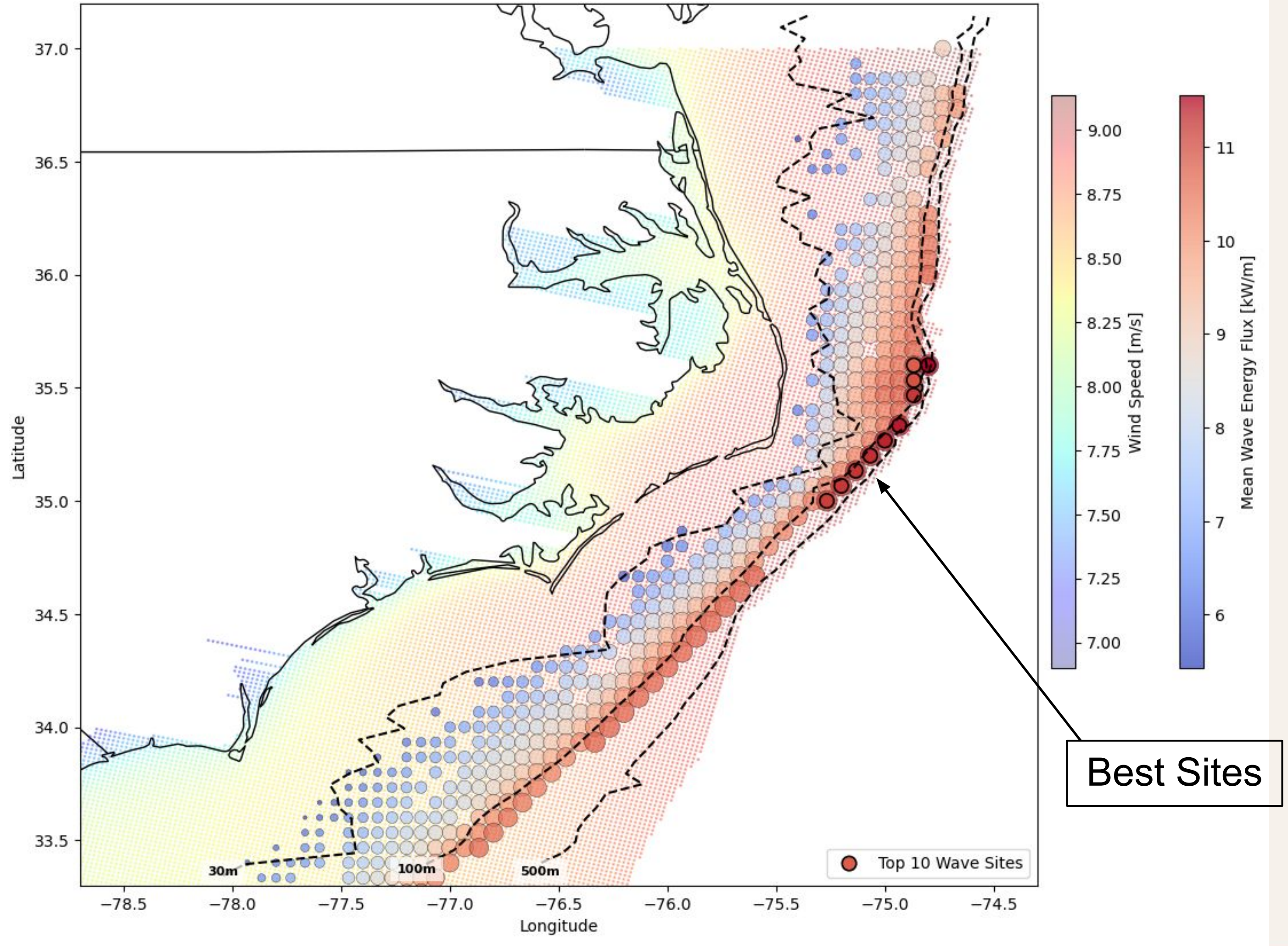
Columns are different wave energy periods

Rows are different significant wave heights

Hs/Te	3.88	4.74	5.6	6.47	7.33	8.19	9.05	9.91
0.25	0.041	0.058	0.028	0.099	0.206	0.165	0.094	0.044
0.75	1.354	2.812	2.297	2.16	4.996	3.53	1.546	0.682
1.25	4.463	5.712	6.072	4.014	4.741	3.75	1.901	0.988
1.75	0.85	5.109	4.49	3.222	2.399	1.92	1.497	0.762
2.25	0.039	1.238	3.546	2.633	1.714	0.913	0.713	0.41
2.75	0	0.14	1.406	1.722	1.249	0.795	0.454	0.242
3.25	0	0.019	0.245	0.773	0.704	0.608	0.283	0.173
3.75	0	0	0	0.237	0.366	0.294	0.193	0.132
4.25	0	0	0	0.03	0.162	0.193	0.171	0.052

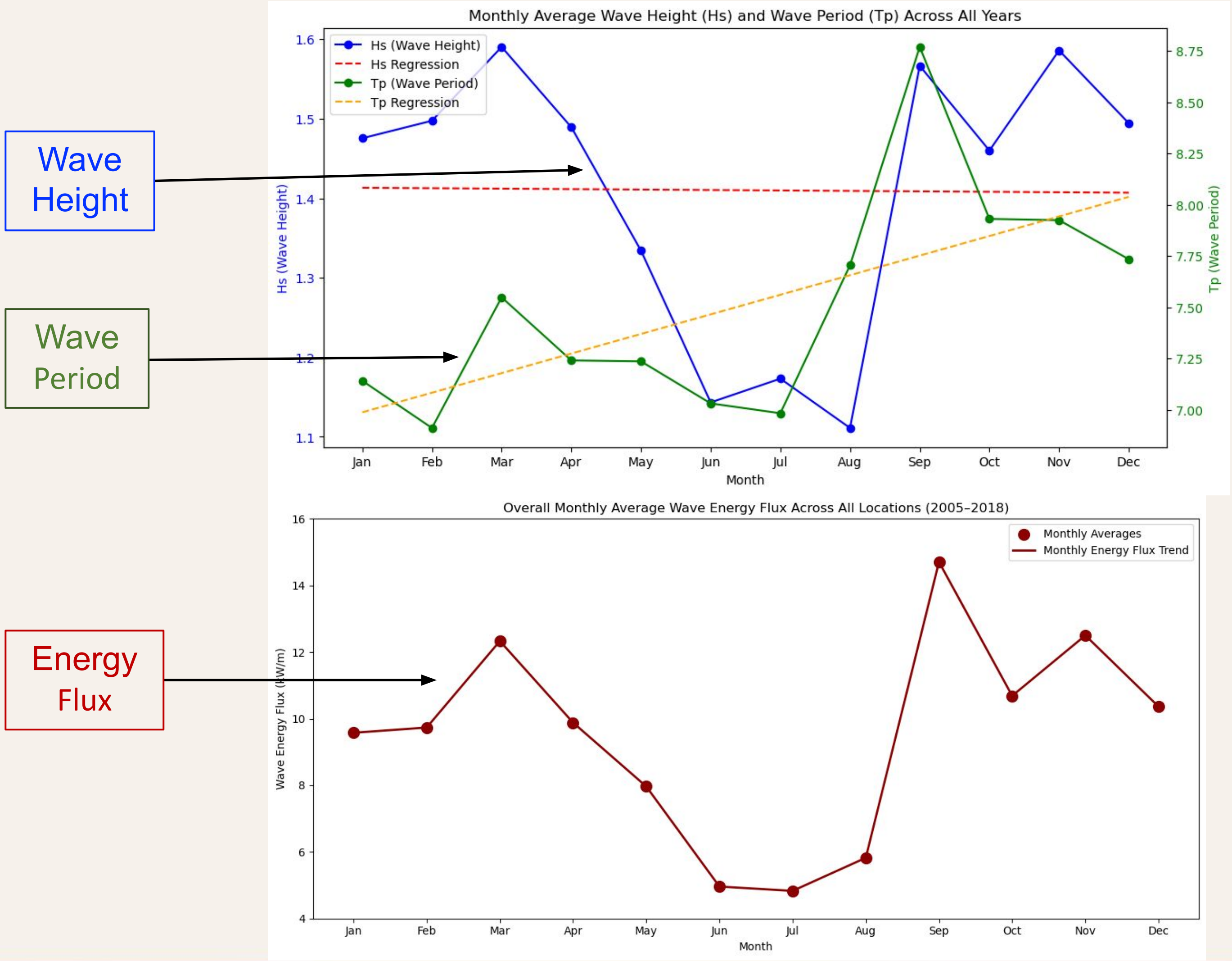
Optimal WEC Deployment Sites

- **Optimal WEC Deployments Sites**
  - These sites were selected based on **the highest weighted average WEC mechanical power outputs**, incorporating the effects of mooring forces.
- **Site Variability Captured via Standard Deviation**
  - **Larger circles highlight locations with more fluctuation** - key for reliability modeling and minimizing energy variation
- **Wave Energy Flux**
  - **Resource intensity increases significantly moving offshore (< 200m)**
  - Highest flux concentrated along the continental shelf break



Seasonality Behavior

- **Clear Seasonal Signal in Wave Dynamics**
  - Monthly trends show **significant variation** in wave height, period, and energy flux **across the year**
- **Peak Resource Availability in Late Summer / Early Fall**
  - September exhibits the highest energy flux, driven by elevated wave activity – during hurricane season
- **Energy Flux Trend**
  - June and July mark the lowest generation potential with an overall **yearly average of ~9.5 kW/m**.



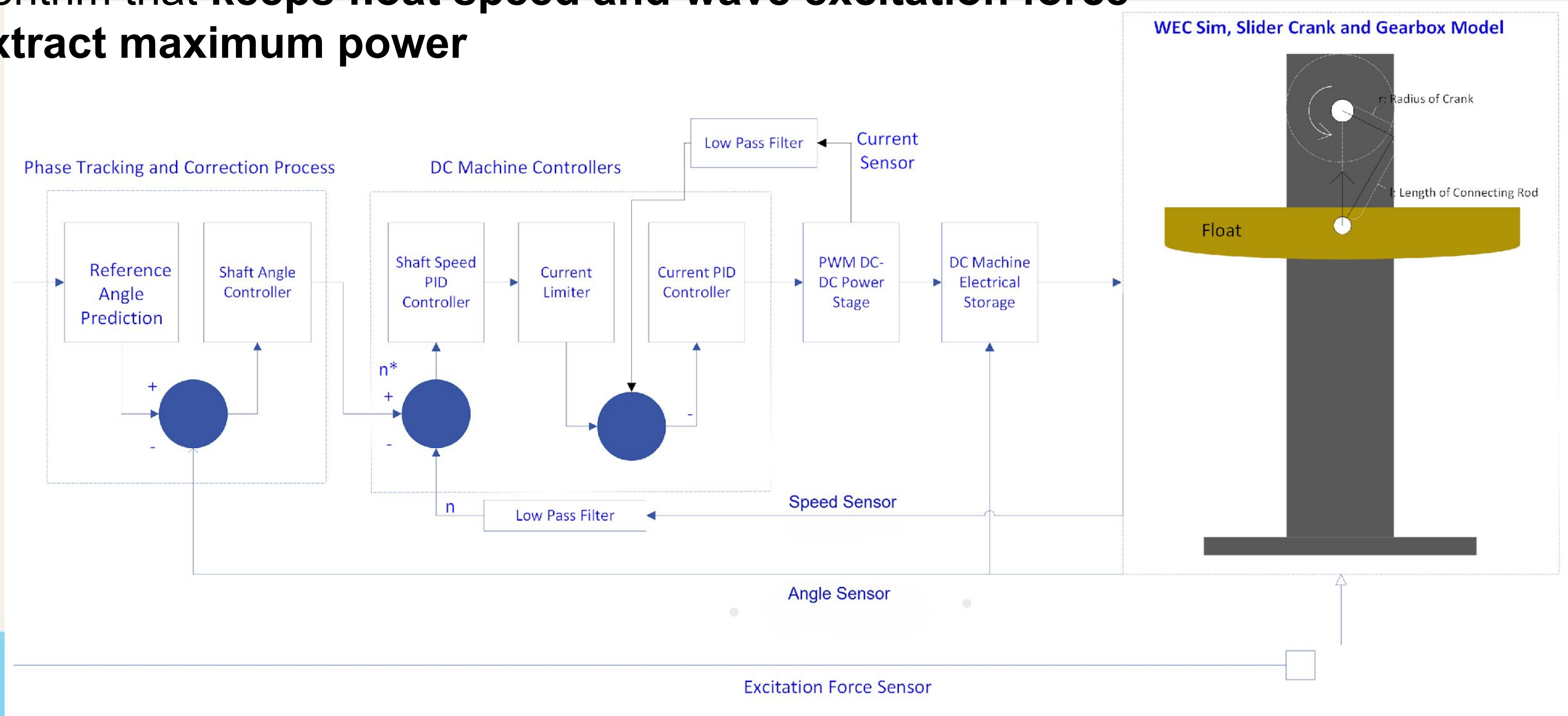
Wave Energy Converter Adaptation

Baseline WEC: Sandia RM3

Wave Energy Controller Model

- **MATLAB/Simulink-based model integrates a two-body point-absorber** system with a slider crank linkage to optimize energy conversion
- The **crankshaft transforms heave motion into unidirectional rotational motion**, driving the generator through a gearbox and power electronics converter
- Reactive control algorithm that **keeps float speed and wave excitation force phase aligned to extract maximum power**

Figure: Slider crank WEC control system block diagram



Best Sites for All WEC Design Scales

- Best 12 sites selected by **weighted average mechanical power with mooring**
- These sites **were chosen because they have the highest mechanical power outputs with taut mooring**

making them → **most efficient sites for electricity generation**

- Each scale consists of 10 selected sites
- Due to differences in scaling, a total of **12 unique sites were identified** across all scales

Lat/Long	Full Scale	Half Scale	1 by 3 Scale
35.60/-74.80	✓	✓	✓
35.47/-74.87	✓	✓	✓
35.33/-74.93	✓	✓	✓
35.27/-75.00	✓	✓	✓
35.20/-75.07	✓	✓	✓
35.13/-75.13	✓	✓	✓
35.07/-75.20	✓	✓	✓
35.00/-75.27	✓	✓	✓
34.67/-75.60	✓	X	X
34.53/-75.73	✓	X	X
35.53/-74.87	X	✓	✓
35.40/-74.93	X	✓	✓

Mechanical Power Outputs Across Different Scales

- **Mechanical power outputs** analyzed across different scales for a lossless WEC
- **Top-performing sea sites** identified with mooring effects included in power calculations

Table: Mechanical Power Outputs with Mooring for the Top 7 Sea Sites Across Different Scales

Lat/Long	1/1 Scale Power Output-Mooring (kW)	1/2 Scale Power Output-Mooring (kW)	1/3 Scale Power Output-Mooring (kW)	Capture Width Ratio (1x1 / 1x2 / 1x3)
35.3/-75.0	124.95	48.20	18.45	0.57 / 0.44 / 0.25
35.6/-74.8	124.33	47.83	18.30	0.57 / 0.44 / 0.25
35.2/-75.1	124.08	47.95	18.38	0.57 / 0.44 / 0.25
35.0/-75.3	123.91	47.28	18.14	0.57 / 0.44 / 0.25
35.1/-75.2	123.63	47.63	18.26	0.57 / 0.44 / 0.25
35.1/-75.1	123.30	47.75	18.32	0.57 / 0.44 / 0.25
35.5/-74.9	121.67	46.99	18.12	0.57 / 0.44 / 0.25

Joint Probability Distribution (JPD) for SAM

Power output matrices were created for **all three scales**

- Electrical power output matrices (with losses) were created for all three scales
- **Significant Wave Height H_s (m):** 0.25 to 9.75 (0.5m increments)
- **Wave Energy Period T_e (s):** 0.43 to 17.67 (21 values)
- JPD below 0.10% were ignored when analyzing **Joint Probability Distribution (JPD)**

Table: Joint Probability Distribution (JPD) as displayed by SAM

Hs = significant wave height (m) \ Te = wave energy period (s)	0.43	1.29	2.16	3.02	3.88	4.74	5.6	6.47	7.33	8.19	9.05	9.91	10.78	11.64	12.5	13.36	14.22	15.09	15.95	16.81	17.67
0.25	0	0	0	0.033	0.041	0.058	0.028	0.099	0.206	0.165	0.094	0.044	0.025	0.014	0.003	0	0	0	0	0	0
0.75	0	0	0.055	1.043	1.354	2.812	2.297	2.16	4.996	3.53	1.546	0.682	0.349	0.171	0.088	0.019	0.014	0.017	0.014	0.008	0.011
1.25	0	0	0	0.548	4.463	5.712	6.072	4.014	4.741	3.75	1.901	0.988	0.404	0.151	0.083	0.058	0.017	0.025	0	0	0
1.75	0	0	0	0	0.85	5.109	4.49	3.222	2.399	1.92	1.497	0.762	0.437	0.228	0.091	0.033	0	0	0	0	0
2.25	0	0	0	0	0.039	1.238	3.546	2.633	1.714	0.913	0.713	0.41	0.242	0.113	0.116	0.03	0	0	0	0	0
2.75	0	0	0	0	0	0.14	1.406	1.722	1.249	0.795	0.454	0.242	0.088	0.058	0.058	0.014	0	0	0	0	0
3.25	0	0	0	0	0	0.019	0.245	0.773	0.704	0.608	0.283	0.173	0.066	0.055	0.036	0.008	0	0	0	0	0
3.75	0	0	0	0	0	0	0	0.237	0.366	0.294	0.193	0.132	0.044	0.025	0.03	0.039	0	0	0	0	0
4.25	0	0	0	0	0	0	0	0.03	0.162	0.193	0.171	0.052	0.077	0.014	0.017	0.014	0	0	0	0	0
4.75	0	0	0	0	0	0	0	0	0.05	0.138	0.102	0.047	0.019	0.022	0.017	0.014	0	0	0	0	0
5.25	0	0	0	0	0	0	0	0	0.014	0.055	0.072	0.036	0.017	0.014	0.011	0.011	0	0	0	0	0
5.75	0	0	0	0	0	0	0	0	0	0.033	0.033	0.025	0.019	0.019	0.003	0.006	0	0	0	0	0
6.25	0	0	0	0	0	0	0	0	0	0	0.03	0.028	0.006	0	0.014	0.017	0	0	0	0	0
6.75	0	0	0	0	0	0	0	0	0	0	0.011	0.019	0	0	0	0	0	0	0	0	0
7.25	0	0	0	0	0	0	0	0	0	0	0	0.011	0	0	0	0	0	0	0	0	0
7.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Electrical Power Ratings for Full Scale

Approach

Highest recorded power output was 1094.58 kW, but **three different upper limits (858, 572, 286 kW)** were used to analyze the power distribution under constrained conditions

Table: Full Scale Power Output Matrix

Hs/Te	6.47	7.33	8.19	9.05	9.91	10.78	11.64	12.5	13.36
0.25	0	0	0	0	0	0	0	0	0
0.75	0	0	0	0	20.83	38.66	42.97	41.61	35.4
1.25	0	0	60.94	105.71	126.38	143.3	140.73	132.83	119.34
1.75	0	101.95	172.96	212.91	228.15	243.4	233.86	218.96	198.12
2.25	103.55	212.66	282.25	316.64	326.15	338.93	322.37	300.05	271.73
2.75	209.67	320.78	388.47	416.89	420.35	429.86	406.2	376.06	340.17
3.25	313.7	426.13	491.46	513.6	510.79	516.11	485.59	447.1	403.51
3.75	415.55	528.72	591.29	607.15	597.77	597.82	560.4	513.05	461.78
4.25	515.05	628.61	688.5	697.55	680.79	674.17	630.73	574.06	515.02
4.75	0	725.71	782.18	784	760.06	744.58	696.36	630.04	563.34
5.25	0	820.83	872.71	866.9	835.2	815.11	757.36	681.11	606.98
5.75	0	0	960.06	946.1	906.01	879.89	813.8	727.46	646.24
6.25	0	0	0	1021.02	972.91	940.11	866	769.46	681.45
6.75	0	0	0	1091.51	1035.68	996.31	0	0	0
7.25	0	0	0	0	1094.58	0	0	0	0

Power Ratings Thresholds

Purpose of These Limitations in the Power Matrix:

- **Investigate the impact of various power ratings on overall energy production**
- **Standardize cost analysis** for different scales by maintaining a consistent cost-per-watt metric
- This approach ensures a more structured analysis of power generation at different scales and allows for meaningful comparisons between full-scale, half-scale, and 1/3-scale systems

Table: Power Ratings for Each Scale

Full Scale	Half Scale	1/3 Scale
1094.58 kW	127.23 kW	34.084 kW
858 kW	63.62 kW	17.042 kW
572 kW	31.81 kW	8.521 kW
286 kW	-	-

Capital Costs and Scaling for Array Configurations

Half Scale:

- **Array Sizes**:
  - 10x10 array with a total of 100 Wave Energy Converters (WECs)
  - 15x18 array with a total of 270 Wave Energy Converters (WECs)
- **Structural Costs:** Assembly costs reduced by 1/2 (half) in reference to the full scale
- **Power Limits:** 3 power ratings
- **Comparisons:** 6 total comparisons (2 array sizes and 3 power ratings)

1/3 Scale:

- **Array Sizes**:
  - 10x10 array with a total of 100 Wave Energy Converters (WECs)
  - 25x26 array with a total of 650 Wave Energy Converters (WECs)
- **Structural Costs**: Assembly costs reduced by 1/3 (one-third) in reference to the full scale
- **Power Limits:** 3 power ratings
- **Comparisons**: 6 total comparisons (2 array sizes and 3 power ratings)

System Advisor Model Cost Calculations

System Advisor Model

1. Structural Assembly Cost:

$$C_{structural} = \frac{\left(\frac{\text{Structural Assembly Cost}_{\text{Full Scale}}}{100} * \text{Array Size}\right)}{\text{Wave Generator Scale}^{\text{Cost Scaling Exponent}}}$$

Full Scale Cost: $236,938,161
Cost scaling Exponent = 2

2. Power Take-Off (PTO) Cost:

$$C_{PTO} = \frac{\left(\text{PTO Cost}_{\text{Full Scale}} * \frac{\text{Power Rating}}{100} * \text{Array Size}\right)}{286}$$

Full Scale Cost: $52,489,652 for 286 kW

3. Mooring Cost:

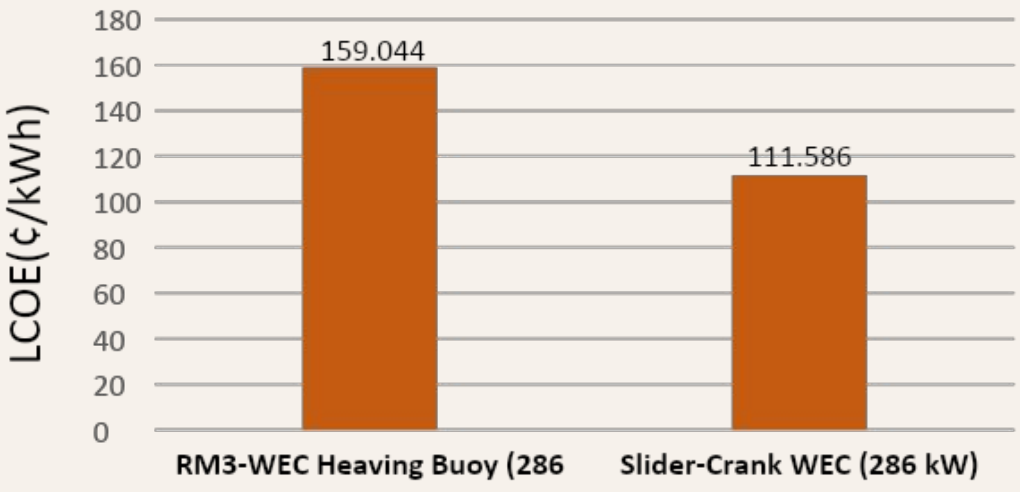
$$C_{mooring} = \frac{\left(\text{Mooring Cost}_{\text{Full Scale}} * \frac{\text{Power Rating}}{100} * \text{Array Size}\right)}{360}$$

Full-scale cost: $93,918,662 for 360 kW based on RM5 – WEC taut mooring

4. Total Device Cost:

$$C_{total} = C_{structural} + C_{PTO} + C_{mooring}$$

LCOE Results for Full Scale RM3 (10x10 array)



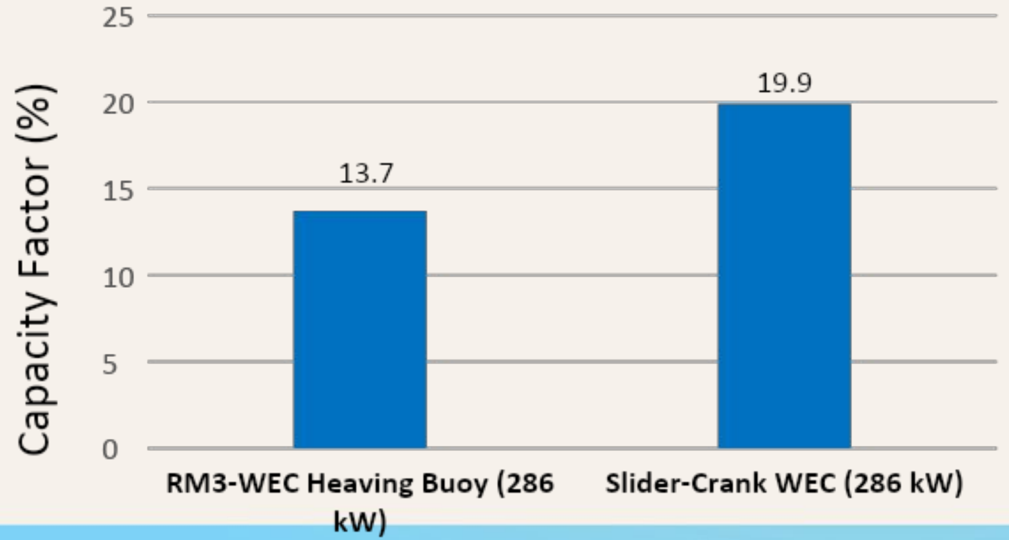
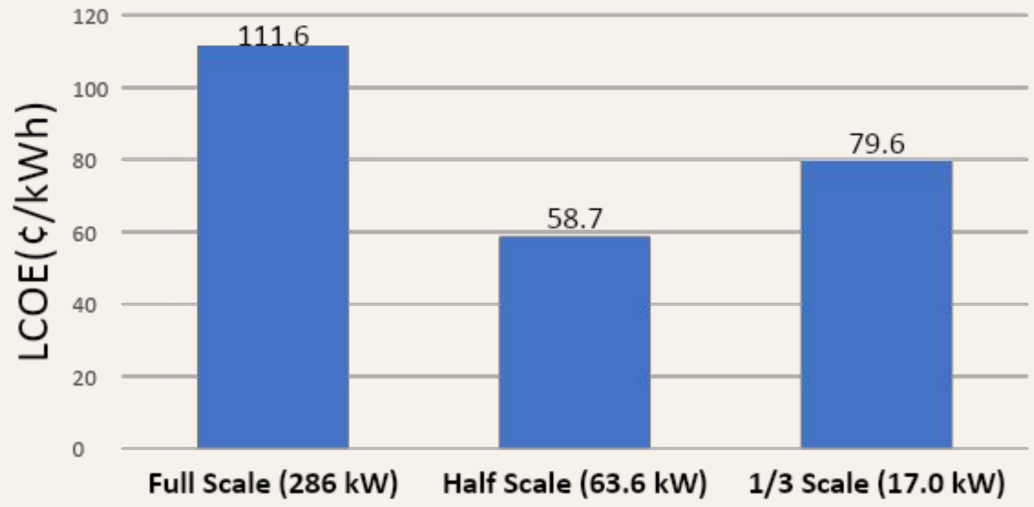
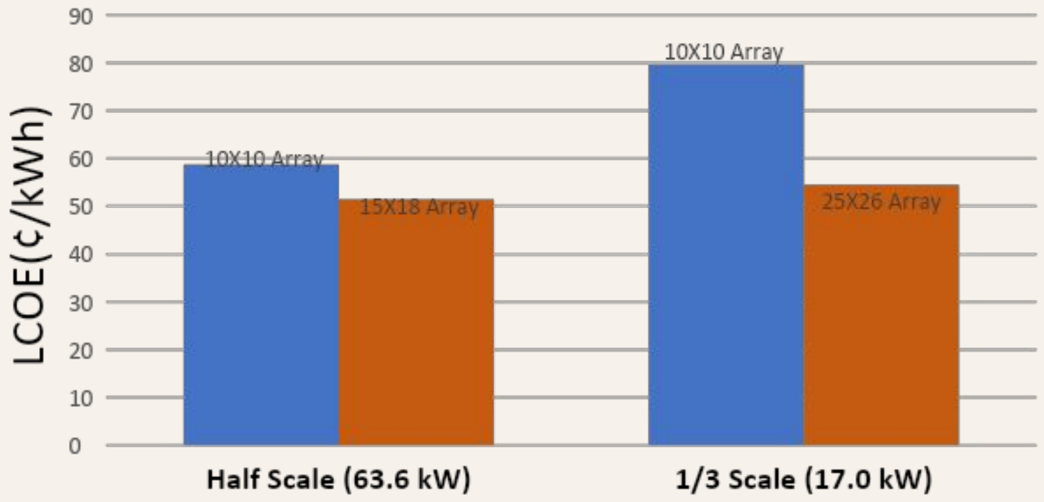


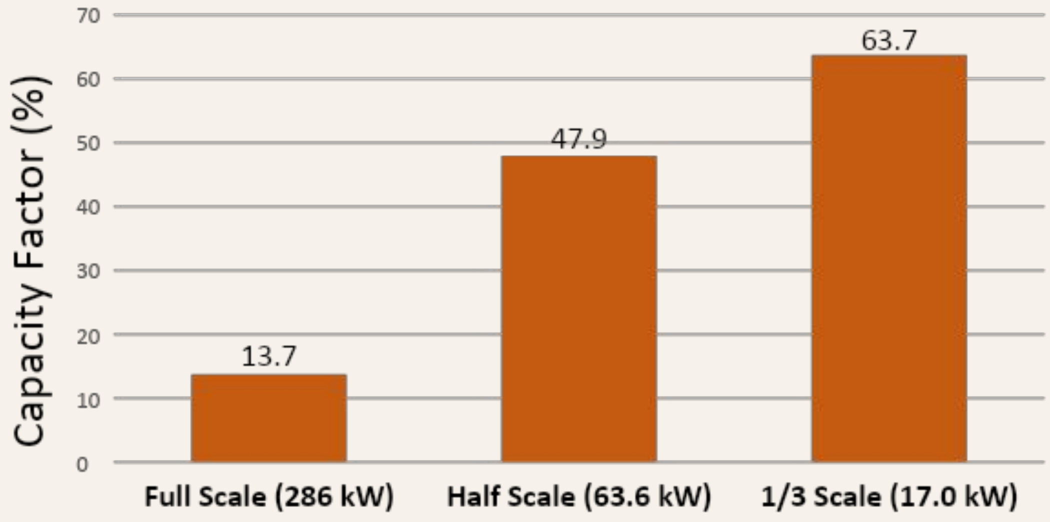
Table: LCOE(¢/kWh) Results for Full Scale

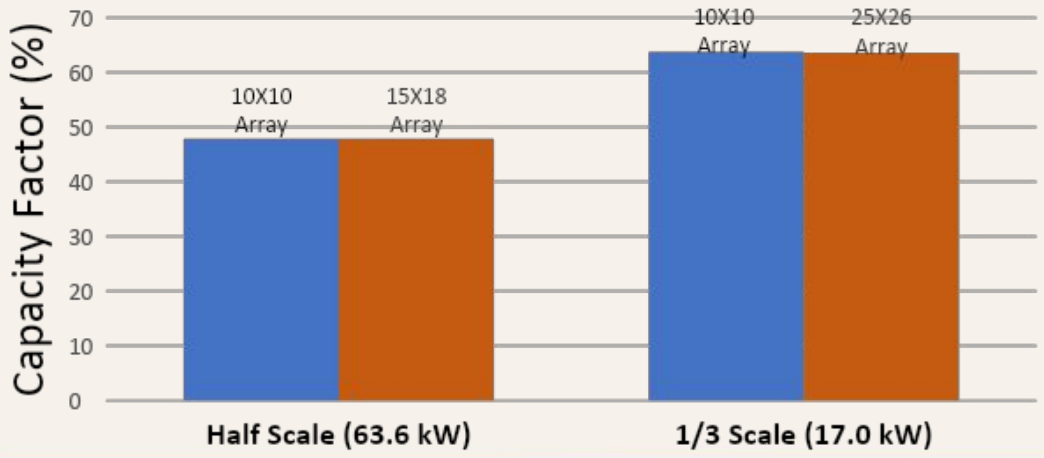
286 kW Rating		572 kW Rating		858 kW Rating		1094 kW Rating	
LCOE (¢ /kWh)	Capacity Factor (%)	LCOE (¢ /kWh)	Capacity Factor (%)	LCOE (¢ /kWh)	Capacity Factor (%)	LCOE (¢ /kWh)	Capacity Factor (%)
111	20	126	12	155	9	183	7
114	19	131	12	162	8	191	6
111	20	128	12	158	8	186	7
110	20	127	12	157	8	186	7
111	20	128	12	159	8	187	7
111	20	129	12	160	8	189	7
111	20	129	12	160	8	189	7
111	20	129	12	160	8	189	7
113	20	132	12	164	8	193	6
113	20	133	12	165	8	195	6

LCOE and Capacity Factor Results Across Different Scales and Array Sizes









Conclusion & Future Work

Preliminary Results Demonstrate Potential Benefits of New WEC Design
The team has shown technical analysis and maps with the potential improvements in CF and LCOE for the new WEC design

We started to analyze the **coordination of the new WEC design with offshore wind** for different systems sizes

Next Steps

Continue to improve on WEC design and array sizing to improve LCOE and CF

Incorporate co-location of wave and wind to further improve system economics

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Thank You!!!

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