Numerical Modeling of a Small-Scale Wave Energy Converter with Inflation Geometry Control

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September 14th, 2022
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Berkeley
UNIVERSITY OF CALIFORNIA

Why use inflation control for a small-scale WEC?

- Many applications including ocean observing and AUV charging
- Need to reliably produce power even in low sea states
  - *Inflate in low sea states to increase power capture and capacity factor*
- "*…an important improvement to pursue is to make the system smaller, as a 10–20% reduction in size would simplify deployment and use significantly.*"

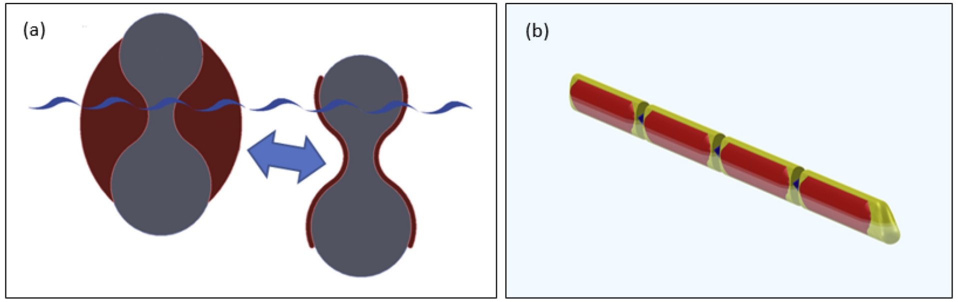
  – Hamilton et al 2021[1] in reference to 10 years of deployments of the 2.64 m diameter point absorber MBARI WEC
  - *Deflated state makes deployment and transportation easier*

- How does inflation control affect annual performance?
- When and how often is the inflation control activated?
- How does inflation control compare with reactive control?

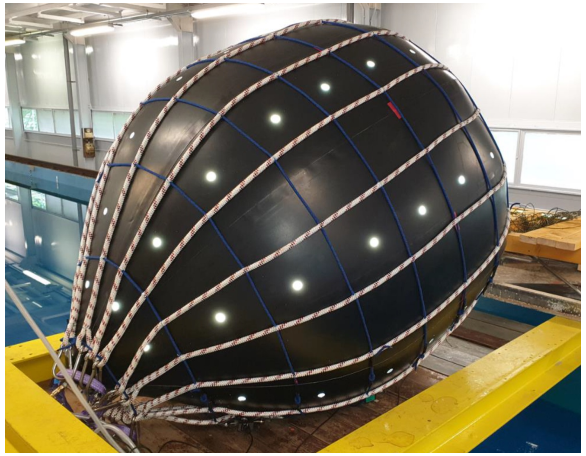
1. Hamilton, A., Cazenave, F., Forbush, D. et al. The MBARI-WEC: a power source for ocean sensing. J. Ocean Eng. Mar. Energy 7, 189–200 (2021). https://doi.org/10.1007/s40722-021-00197-9

Background

- Inflatables have been used in many industries
  - Aerospace, Tunnel flood protection, Marine
- Inflation Geometry Control has been investigated for large WECs
  - Attenuator (Quoceant 2017, Pardonner et al 2020)
  - Two-body point absorber (Ogden et al 2021)
- Inflatables already used in small scale wave energy trials
  - Netbuoy 2018-2022
  - Oneka's Snowflake - U.S. DOE's Waves to Water prize winner



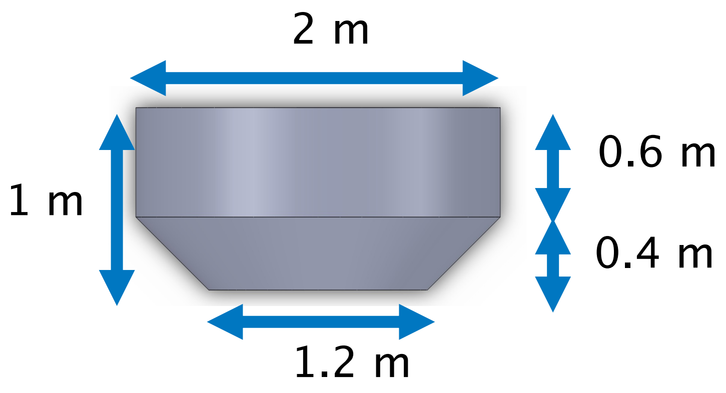
(2017 MASIV – Quoceant - Wave Energy Scotland)



(2020 Netbuoy – Tension Technology International Ltd - Wave Energy Scotland)

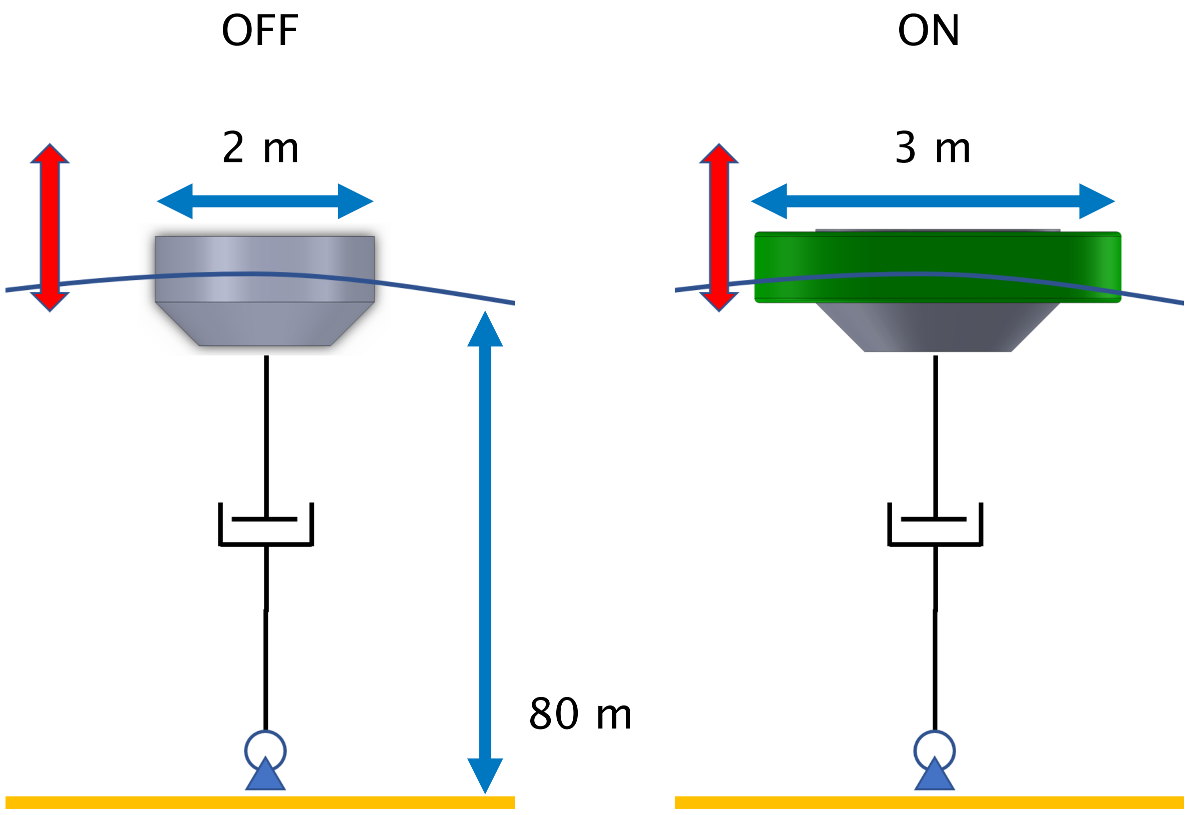
Device Design

- Small-scale heaving point absorber
- Passive PTO control optimized in each sea state
- Inflation control adjusted on sea state basis
  - OFF: rigid core only
  - ON: inflatable extending out from core
- Inflatable pressurized to be rigid[1]



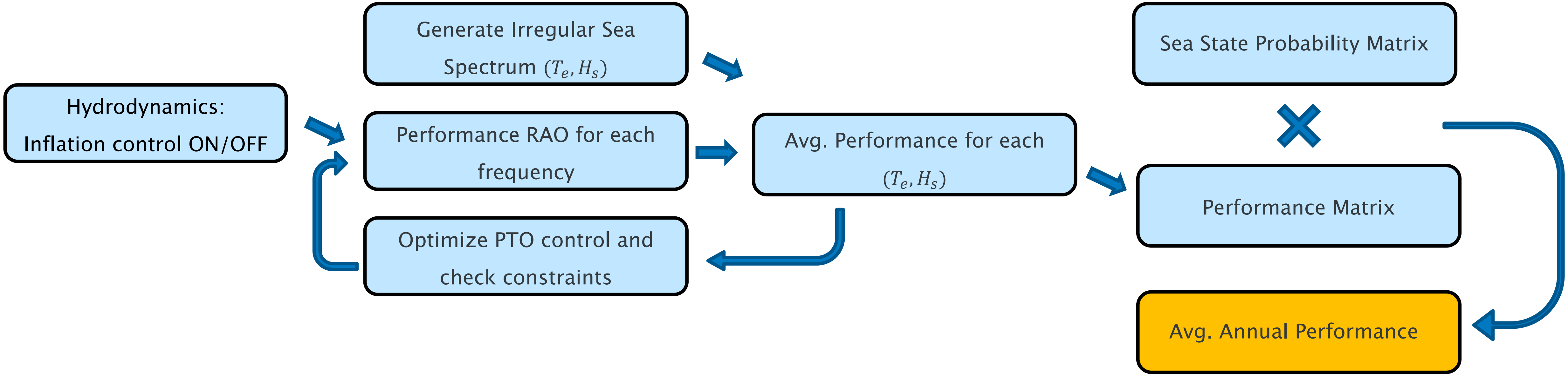
Mass: 750 kg

Inflation Control:

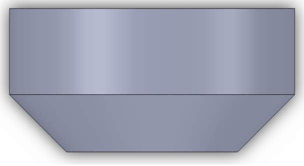


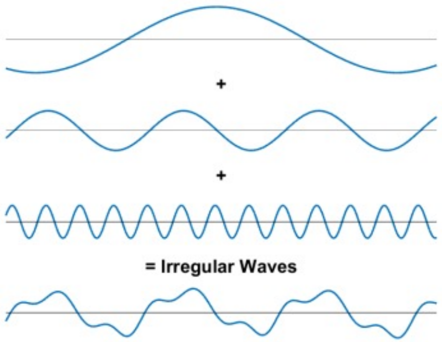
1. Kelly, M., Boerner, T., & Alam, M. "Modeling Comparison of Flexible-inflatable and Rigid Small-scale Heaving Wave Energy Converters". *Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering. Volume 9: Ocean Renewable Energy*. Hamburg, Germany. June 5–10, 2022.

Modeling Approach in the Spectral Domain



- Hydrodynamic coefficients calculated with WAMIT
- PTO coefficients optimized for output power under constraints
  - Sea state average power limit: $P_{O-SS} = \int_0^\infty \left|\frac{P_O(\omega)}{A^2}\right| S^+(\omega)d\omega$
  - Sea state average peak heave amplitude limit: $X_{3-SS} = \frac{5}{4} X_{3-RMS} = \frac{5}{4}\sqrt{\int_0^\infty \left|\frac{X_3(\omega)}{A}\right|^2 S^+(\omega)d\omega}$
- Quadratic viscous damping (linearized for spectral model)
- Spectral model compared well with time-domain model (~+4% average annual power)





Three wave energy sites considered

Joint Probability Diagram (% of year each sea state occurs)

Newport, OR

Sig Wave Height H_s [m] \ Energy Period T_e [s]	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	17.5	18.5
8.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	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	0.1	0.0	0.0	0.0	0.0	0.0	0.0
7.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
6.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
6.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
5.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0
5.25	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0
4.75	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.6	0.3	0.2	0.0	0.0	0.0	0.0	0.0
4.25	0.0	0.0	0.0	0.0	0.0	0.3	1.2	1.2	0.8	0.4	0.2	0.1	0.0	0.0	0.0	0.0
3.75	0.0	0.0	0.0	0.0	0.0	0.8	1.8	1.7	0.9	0.7	0.2	0.1	0.0	0.0	0.0	0.0
3.25	0.0	0.0	0.0	0.0	0.2	1.6	2.6	2.4	1.4	0.7	0.2	0.2	0.0	0.0	0.0	0.0
2.75	0.0	0.0	0.0	0.0	0.7	2.5	3.4	3.3	1.5	0.5	0.4	0.1	0.1	0.1	0.0	0.0
2.25	0.0	0.0	0.0	0.1	1.5	3.7	4.6	3.0	1.5	0.6	0.3	0.1	0.1	0.0	0.0	0.0
1.75	0.0	0.0	0.0	0.7	3.4	6.4	5.2	2.2	1.4	0.6	0.3	0.0	0.0	0.0	0.0	0.0
1.25	0.0	0.0	0.1	1.2	4.8	6.5	5.1	2.4	1.5	0.6	0.1	0.1	0.0	0.0	0.0	0.0
0.75	0.0	0.0	0.0	0.4	0.8	1.2	1.0	0.9	0.6	0.2	0.1	0.0	0.0	0.0	0.0	0.0
0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Navy WETS Oahu, HI

Sig Wave Height H_s [m] \ Energy Period T_e [s]	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	17.5	18.5
8.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	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	0.0	0.0	0.0	0.0	0.0	0.0
7.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.25	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.75	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.25	0.0	0.0	0.0	0.0	0.2	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
2.75	0.0	0.0	0.0	0.0	1.6	1.4	0.7	0.5	0.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0
2.25	0.0	0.0	0.0	1.5	4.4	2.2	1.5	1.1	0.7	0.5	0.2	0.1	0.0	0.0	0.0	0.0
1.75	0.0	0.0	0.5	10.7	8.3	4.8	3.3	2.3	1.5	0.7	0.3	0.1	0.0	0.0	0.0	0.0
1.25	0.0	0.0	4.1	14.0	8.2	5.7	4.1	2.6	1.3	0.5	0.2	0.1	0.0	0.0	0.0	0.0
0.75	0.0	0.0	0.7	1.9	1.9	1.6	0.8	0.4	0.2	0.1	0.0	0.1	0.0	0.0	0.0	0.0
0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Newport, OR

Humboldt Bay, CA

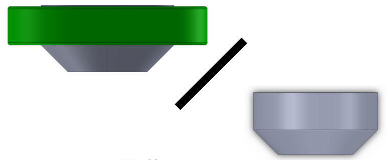
Navy WETS Oahu, HI

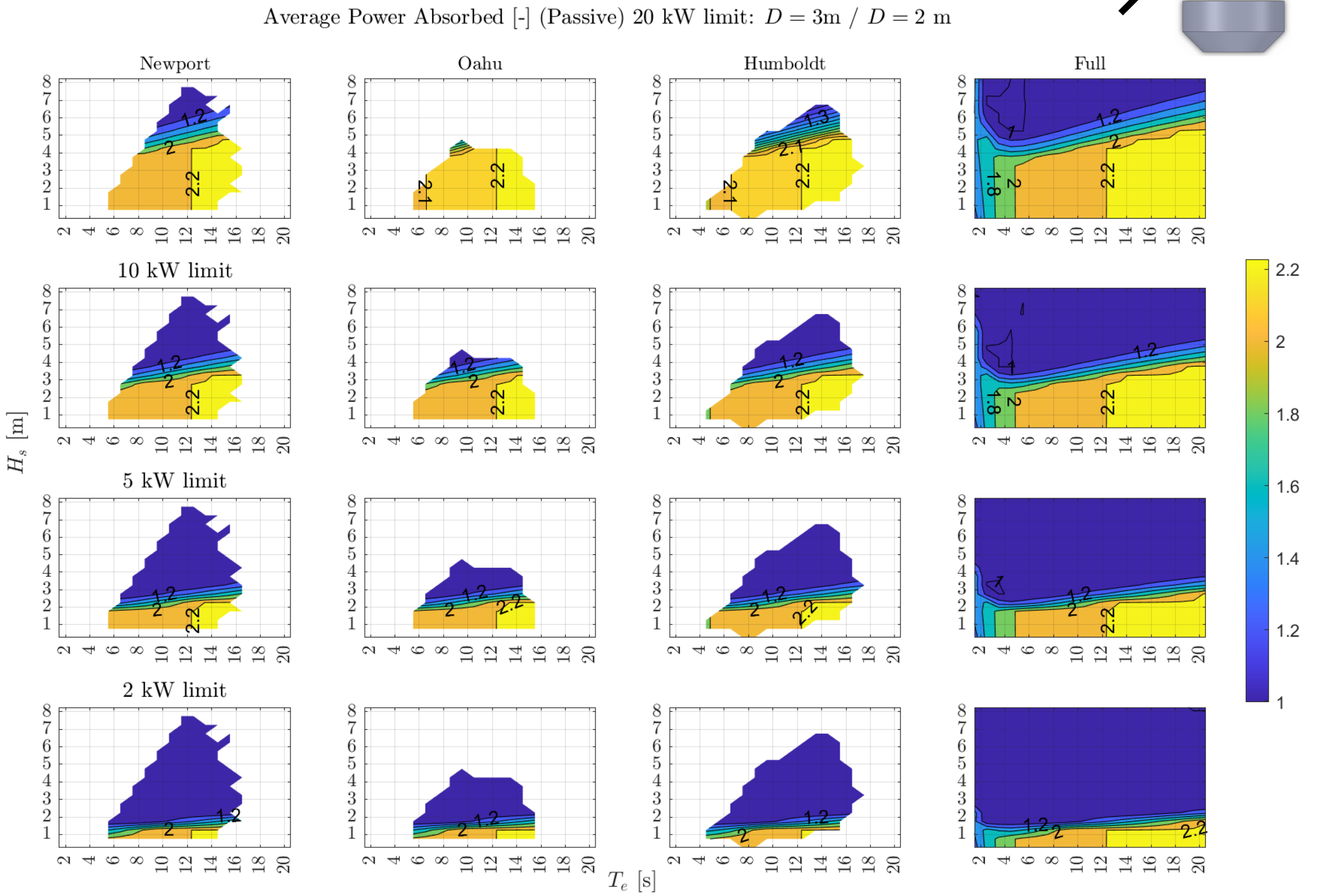
A. Dallman, V. Neary, “Characterization of U.S. Wave Energy Converter (WEC) Test Sites: A Catalogue of Met-Ocean Data.” Septembe

Results

Performance Matrices: Average Peak Power Limits

- Comparing the average power improvement for inflated vs. deflated

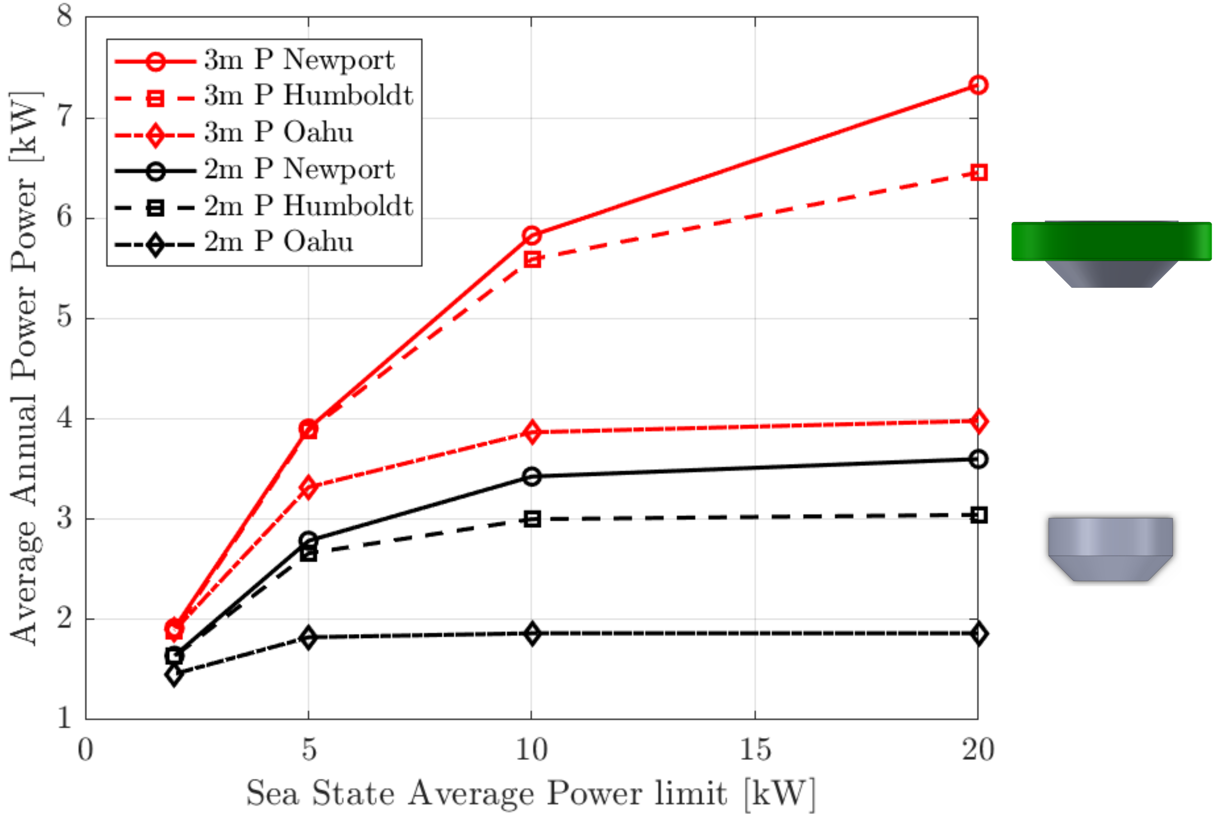


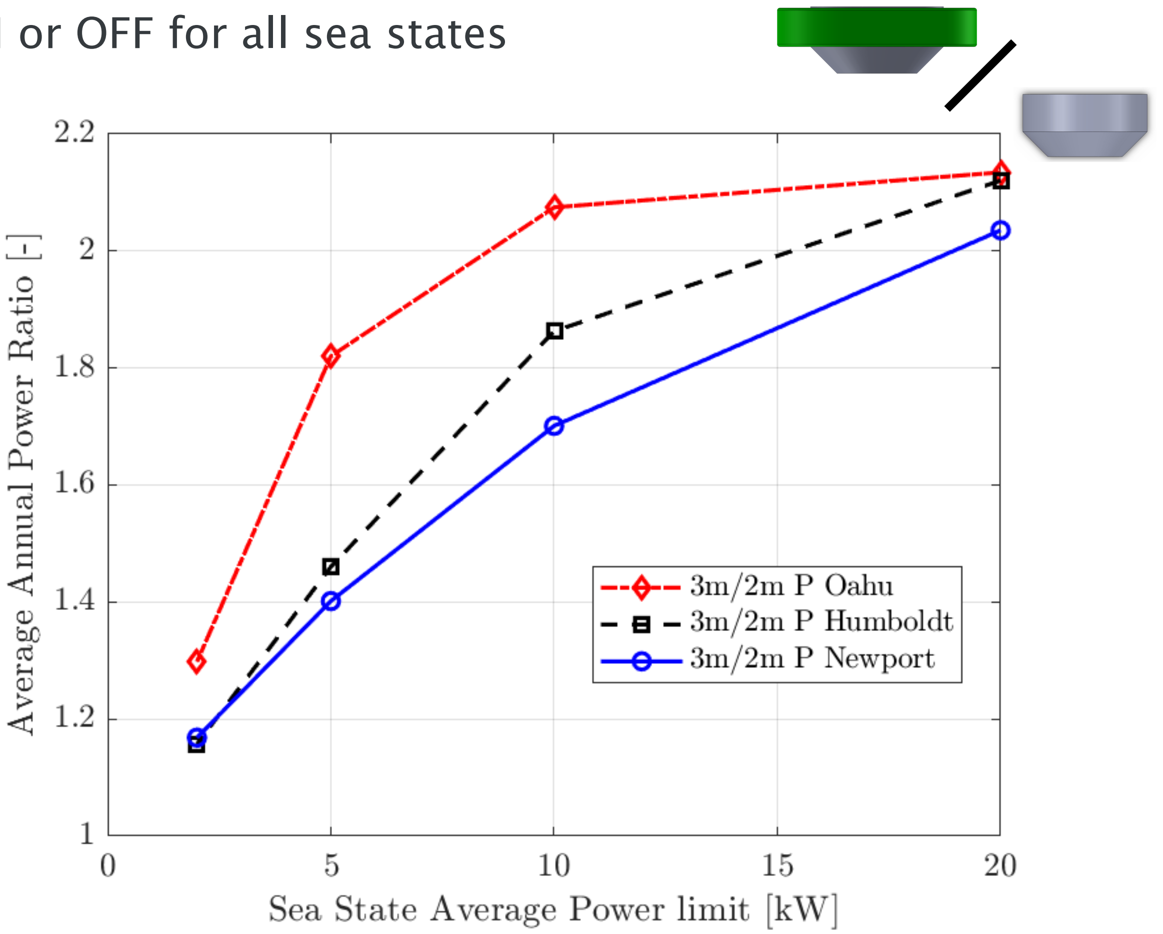


- Inflated state can produce significantly more avg power (2x+)
- Steeper limits → more sea states where inflated and deflated perform similarly

Annual Performance: Average Peak Power Limits

- Comparing the average annual power with inflation control ON or OFF for all sea states

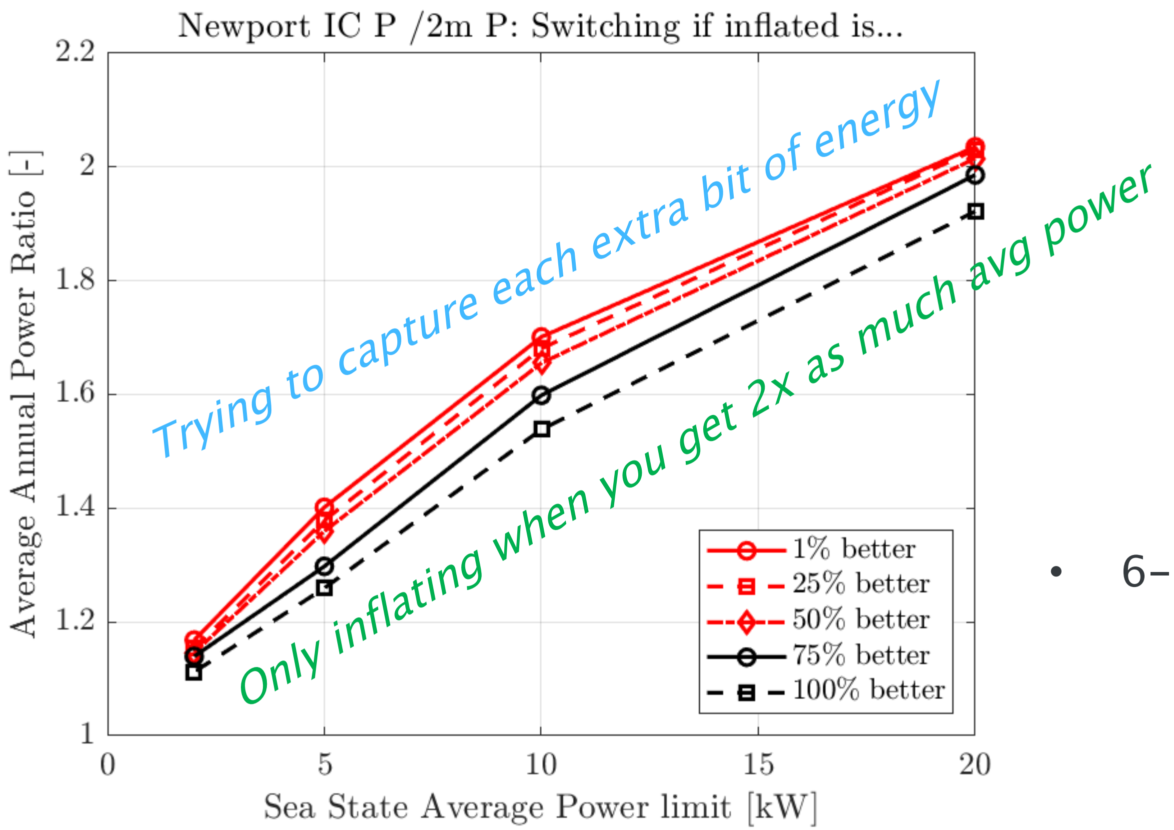




- Inflated configuration produces significant power increases for most average power limits (1.2–2.1x more power)
- Power increases are more pronounced for low energy sites

Annual Performance: When to inflate?

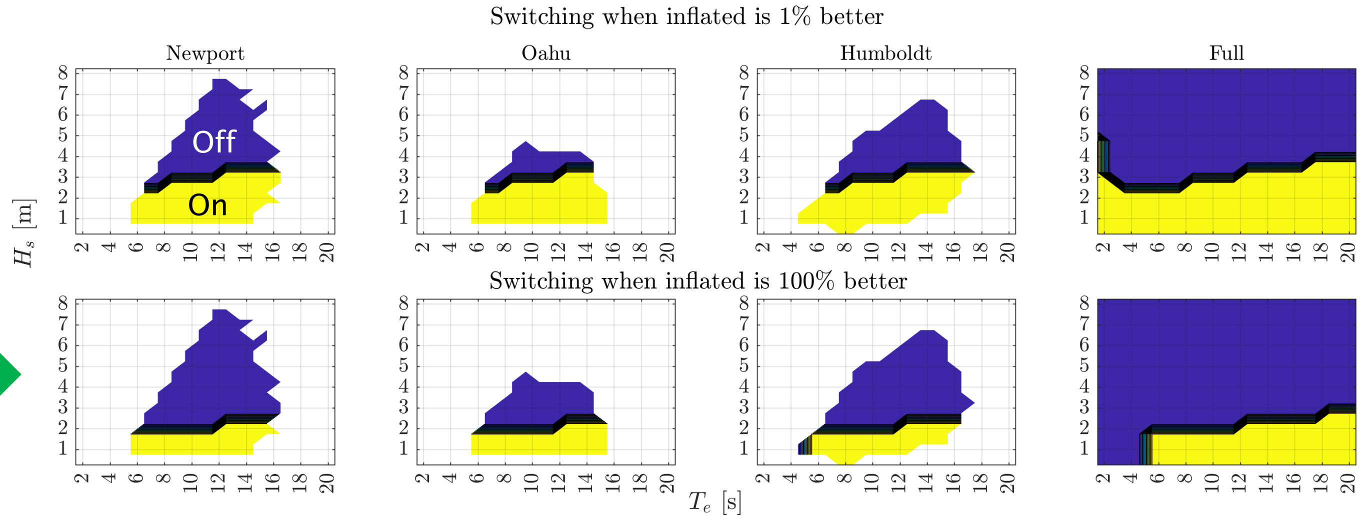
- Comparing different strategies for inflation control (IC) and the average annual power increase over the case of no IC
- Assumed that IC decisions are on a sea state time scale



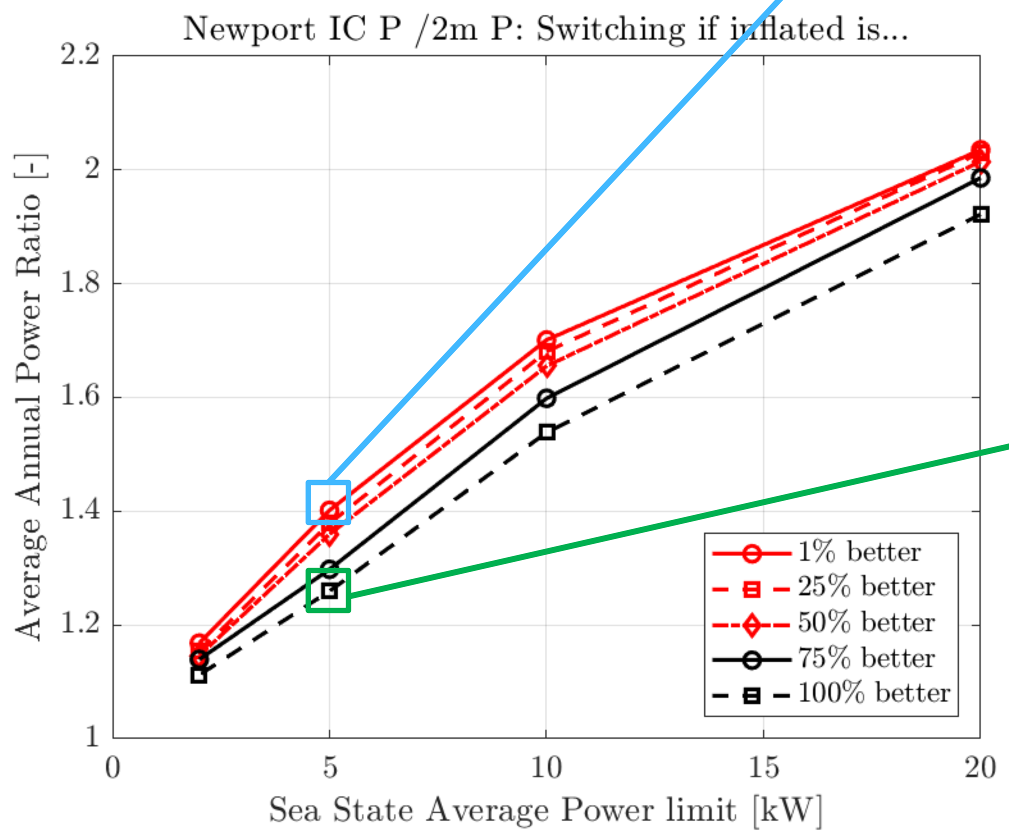
- 6–16% more average power for 1% vs. 100% strategy

5 kW Avg Power Limit: When to inflate?

- Comparing when to initiate inflation control (IC)



Trying to capture each extra bit of energy

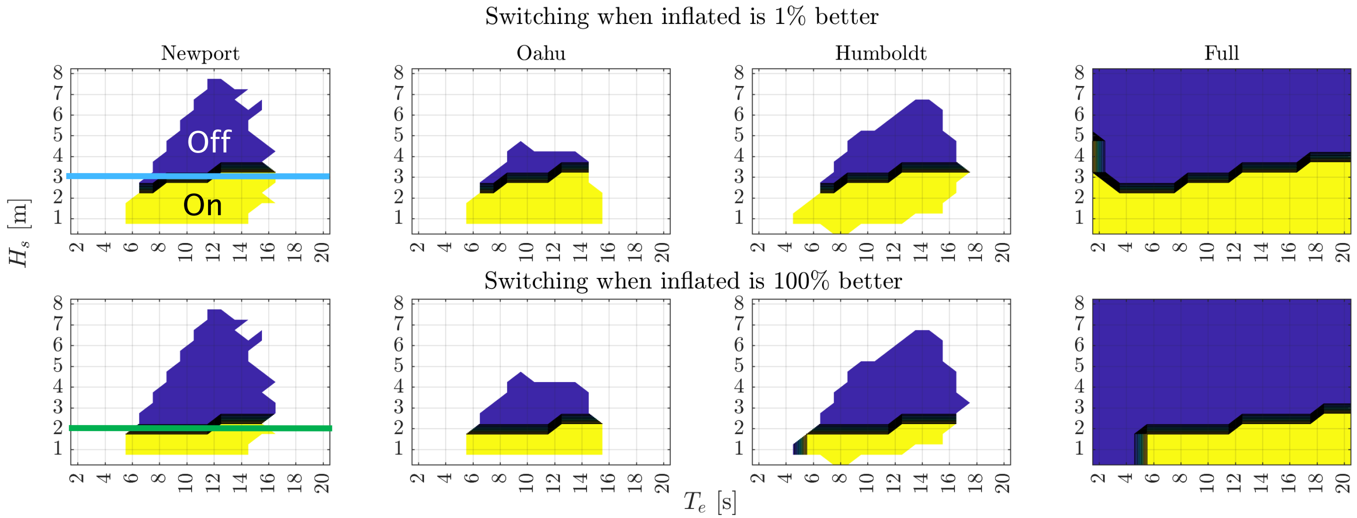


Only inflating when you get 2x as much avg power

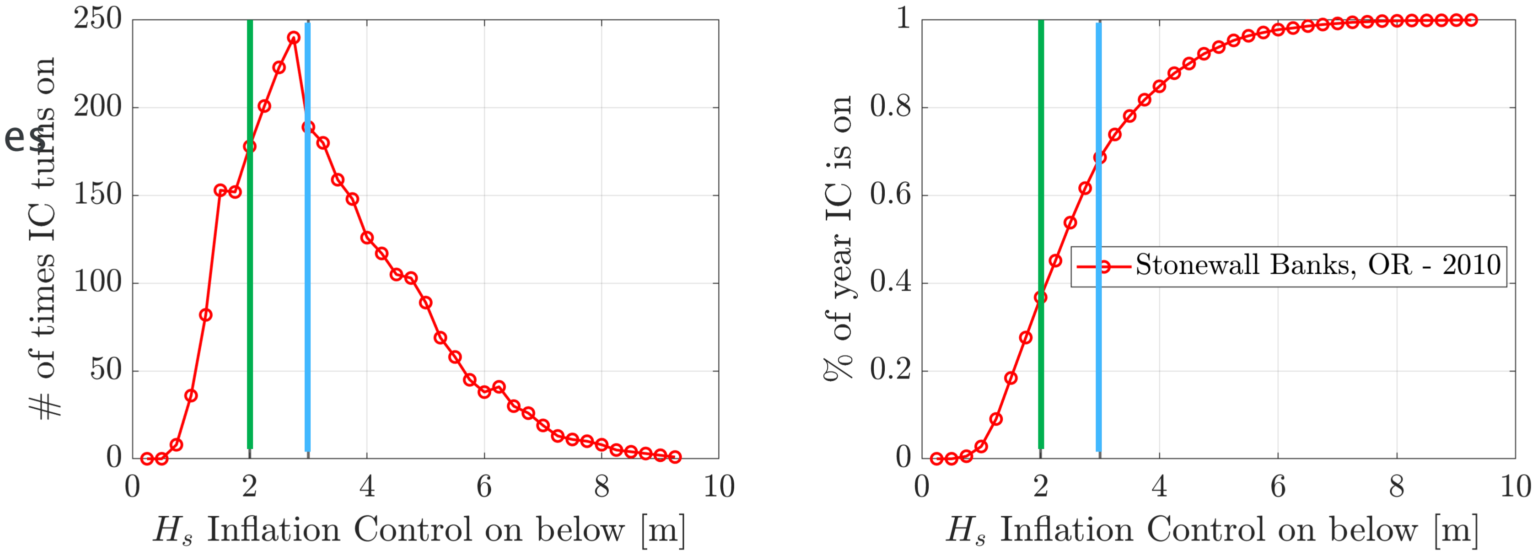
- 6–16% more average power for 1% vs. 100% strategy
- 1% strategy inflates below $H_s \approx 3$ m
- 100% strategy inflates below $H_s \approx 2$ m

5 kW Avg Power Limit: How often is inflation needed?

- Comparing when to initiate inflation control (IC)
  - Inflating for any power increase (1% better)
  - Inflating only for 2x power increase (100% better)



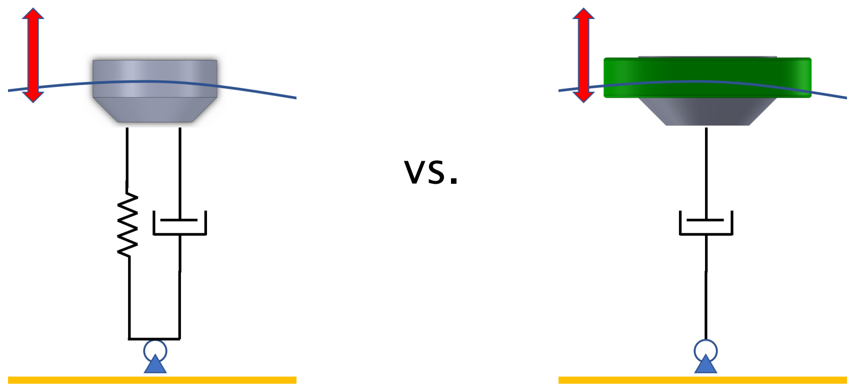
- Considering 1 year of sea state time series data off the coast of Newport, OR in 2010 [1]:



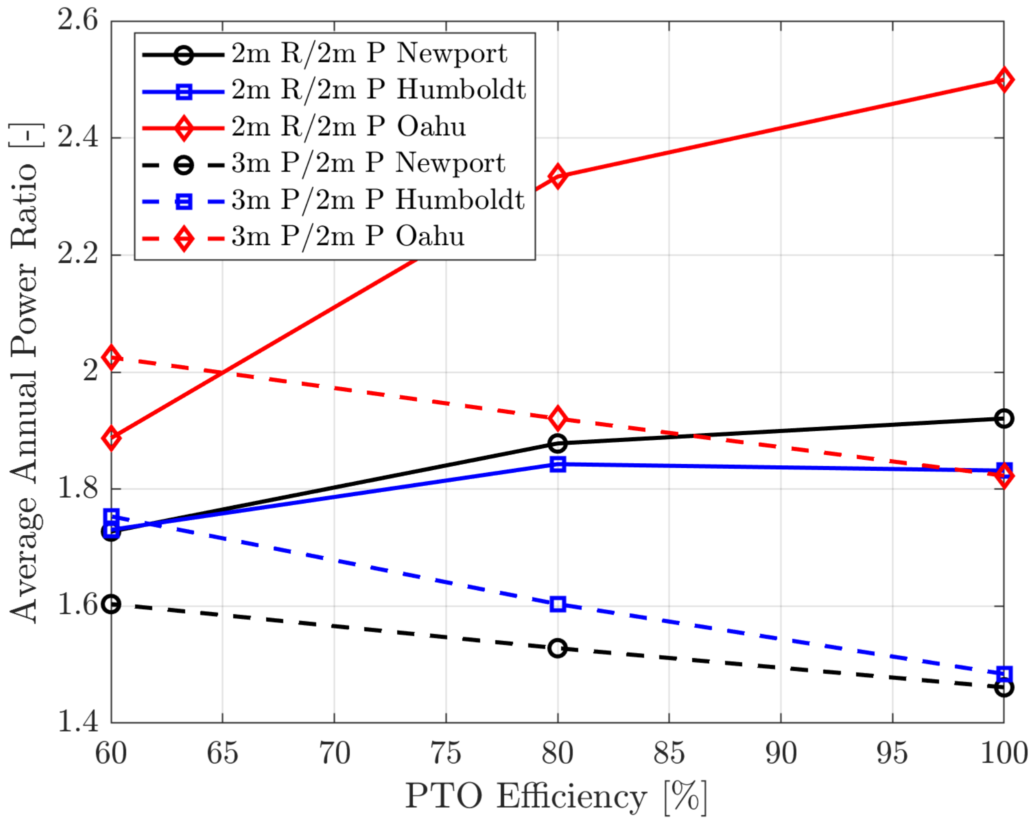
- End up inflating ~ same number of times
- IC active: 70% of year for 1%
- IC active: 40% of year for 100%

1. National Data Buoy Center (www.ndbc.noaa.gov)

Core with Reactive (2 m) Inflated with Passive (3 m)



- Maximizing average output power (constant PTO efficiency)
  - Bi-directional efficiency losses for reactive control [1,2]
- Average peak sea state heave motion limit=1 m



- For high efficiencies, reactive control produces a better improvement over the base case at all locations
- Near 60% PTO efficiency, inflation control is better in terms of power performance for Humboldt and Oahu

1. A.F.O. Falcao, J.C.C. Henriques, Effect of nonideal power take-off efficiency on performance of single- and two-body reactively controlled wave energy converters, Journal of Ocean Engineering and Marine Energy 1 (3) (2015) 273e286.
2. Tom et al. Balancing the Power-to-Load Ratio for a Novel Variable Geometry Wave Energy Converter with Nonideal Power Take-Off in Regular Waves: Preprint. United States: N. p., 2017. Web.

Conclusions

- A small-scale heaving WEC with inflation geometry control was modeled to determine performance at 3 different

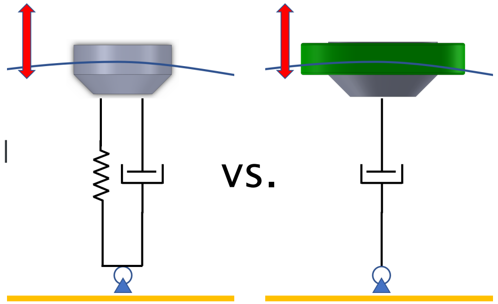
- **How does inflation control affect annual performance?**

- Can produce **1.1x–2.1x more average annual power** than without IC (depending on avg power limit and location)

- **When and how often is the inflation control activated?**

- **IC activated ~200 times**, and is on for **40%–70% of the year** for the case of 2010 off the coast of Newport, OR

- **How does inflation control compare with reactive control?**



- For high PTO efficiencies reactive PTO control can produce **15–55% more power** than inflatio
- Near 60% efficiency, inflation control is up **8% better**
- Constant efficiency considered here but real PTO’s have different dynamics than this

Acknowledgements

- This research was supported in part by an appointment with Marine and Hydrokinetic Graduate Student Research Program sponsored by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, and Water Power Technologies Office. This program is administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by ORAU under DOE contract number DESC0014664. All opinions expressed in this presentation are the author's and do not necessarily reflect the policies and views of DOE, ORAU, or ORISE.

- MRA would like to acknowledge partial support from the American Bureau of Shipping (ABS).