Sheltering effect of various wave energy converter archetypes in arrays

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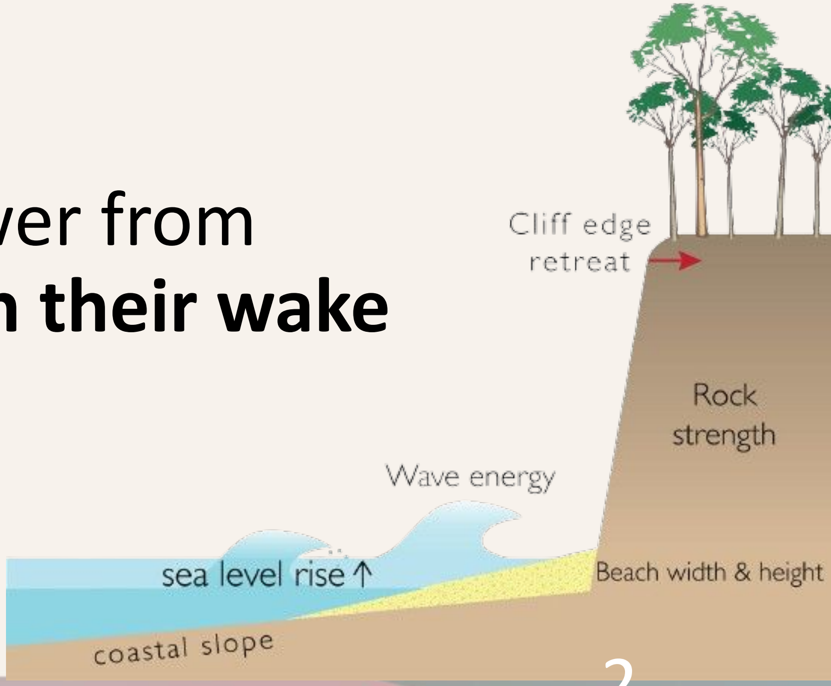
Background → Wave Sheltering

Offshore structures and coastlines face **fatigue damage and deterioration** due to cyclical wave loads[1],[2]

Wave energy converters (WECs) extract power from ocean waves, leaving **lower energy waves in their wake**



[3]

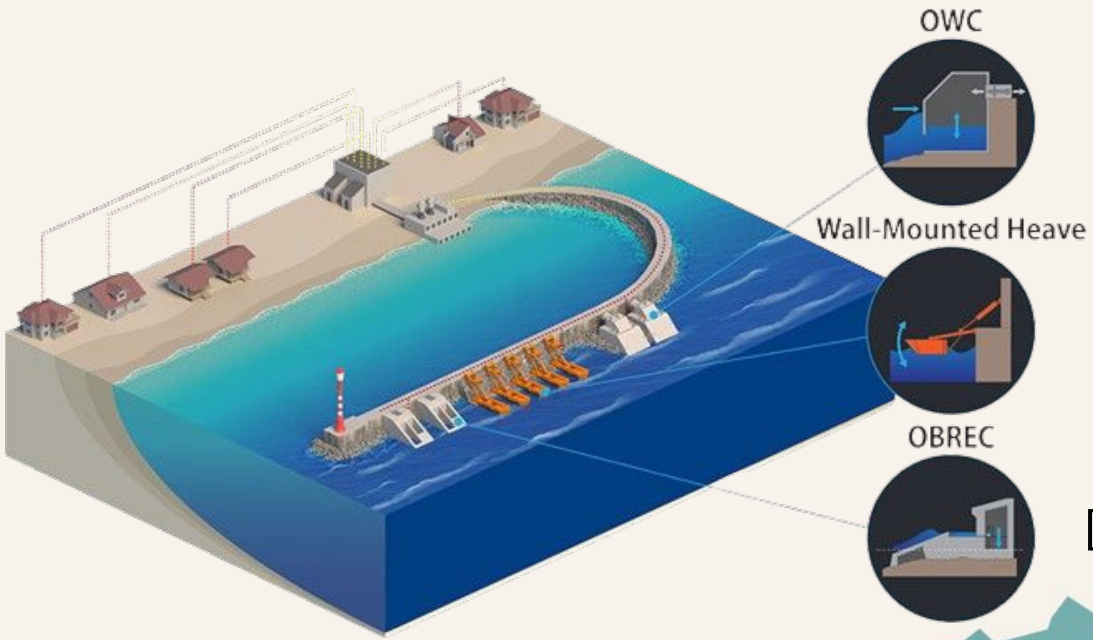
[1] Sun, C., Jahangiri, V., 2019, [2] Häfele et al. 2018, [3] USGS 2023

Background → Wave Sheltering

Studies have investigated the **wave sheltering capabilities of different WECs** for protecting vulnerable coastlines[4],[5],[6],[7], offshore aquaculture farms[8], and offshore wind installations[9],[10],[11]

NREL[12] is working to construct **coastal structure integrated WECs**, which are attached to traditional fixed breakwaters

This presentation focuses specifically on **floating WECs**



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[4] Flanagan, Wengrove, Robertson, 2022, [5] Chang et al. 2016, [6] Contardo et al. 2018, [7] Rusu, Guedes Soares, 2013, [8] Silva, Rusu, Guedes Soares, 2018, [9] Astariz, Perez-Collazo, Abanades, Iglesias, 2015, [10] Clark, Paredes, 2018, [11] Clark, Velarde, Sønderkær Nielsen, 2018, [12] NREL, 2023

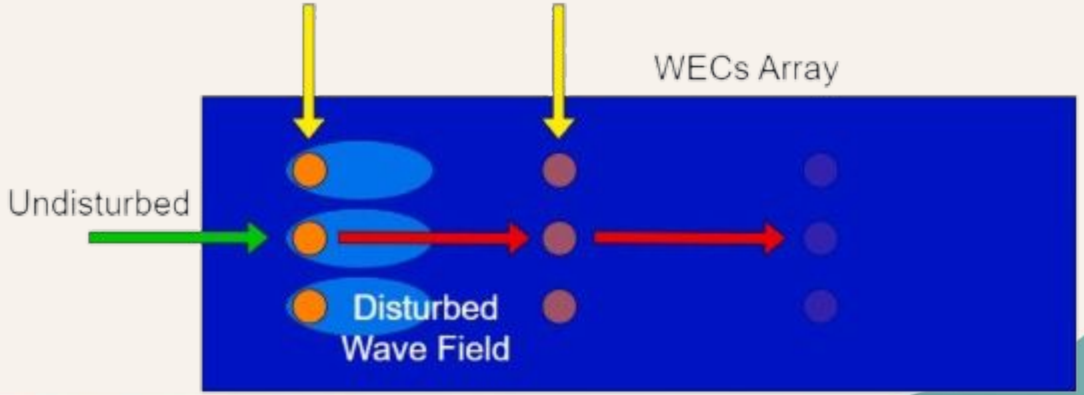
Background → Wave Sheltering

Methods for quantifying this performance rely on **using capture width ratio** to determine how much wave power the device absorbs[4-11],[13]

- This **ignores reflected and dissipated wave energy**, assuming that all energy not absorbed is transmitted

Additionally, WECs are often modeled in isolation, but the end-goal is to deploy WEC arrays

- One study accounted for WEC wakes when considering **array wave sheltering[14], but did not include interactions,** only power available to downstream WECs



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[13] Venugopal, Nemalidinne, Vögler, 2017, [14] Zou et al., 2024

Background → Wave Sheltering

Questions:

1. How do we define WEC wave sheltering capabilities?

2. How do different WEC architectures perform in this metric?

3. How does this change when including array interactions?

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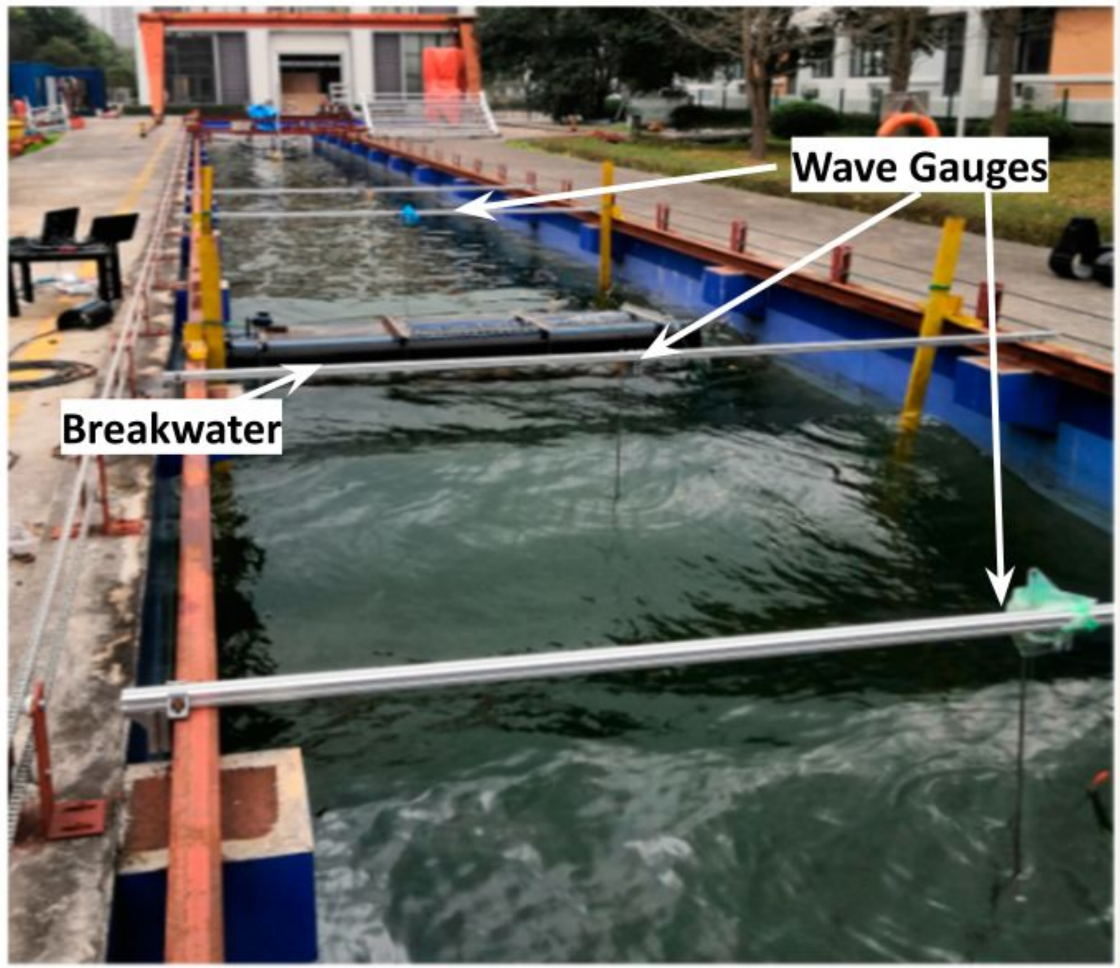
Methodology → Metrics

Standard practice in coastal engineering is to measure wave heights up- and down-stream of a body to determine its dissipative properties[15]

Some WEC studies have employed this method for a WaveCat[16] and a point absorber[17]



[18]

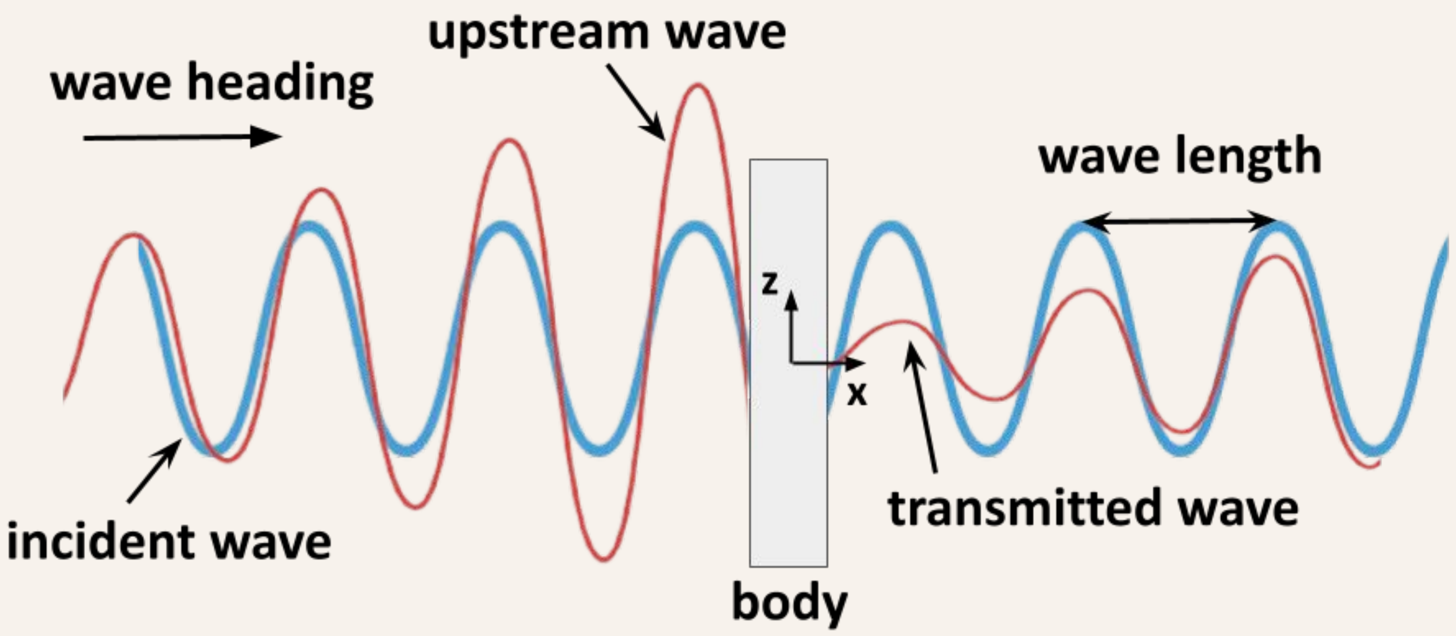
[15] Seelig 1980, [16] Carballo, Iglesias, 2013, [17] Atan et al. 2019, [18] Bao et al. 2022.

Methodology → Metrics

We define performance by the transmission (K_t) and reflection (K_r) coefficients[19]

$$K_t = \frac{|\eta|_{transmitted}}{|\eta|_{incident}}$$

$$K_r = \frac{|\eta|_{upstream}}{|\eta|_{incident}} - 1$$



η: wave elevation

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[19] Seelig, Ahrens, 1981

Methodology → Metrics

The **dissipation coefficient (K_D)** represents **energy that is either dissipated or absorbed** by the WEC and is defined as:

$$K_D = 1 - K_t^2 - K_r^2 \geq 0$$

The **potential power extracted** is defined by Falnes[20] as:

$$P' = J_{inc} - J_r - J_t \quad [kW/m]$$

where J is the wave energy transport

$$J = \frac{\rho g}{4\omega} |A|^2$$

ρ: fluid density
g: gravitational constant
ω: wave frequency [rad/s]
A: wave amplitude

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[20] Falnes, Kurniawan, 2020

Methodology → Metrics

How do we define WEC wave sheltering capabilities?

- K_t and K_r define our device **performance**
- The K_D condition must be met for **energy balance**
- P’ is how we define potential **power extracted**

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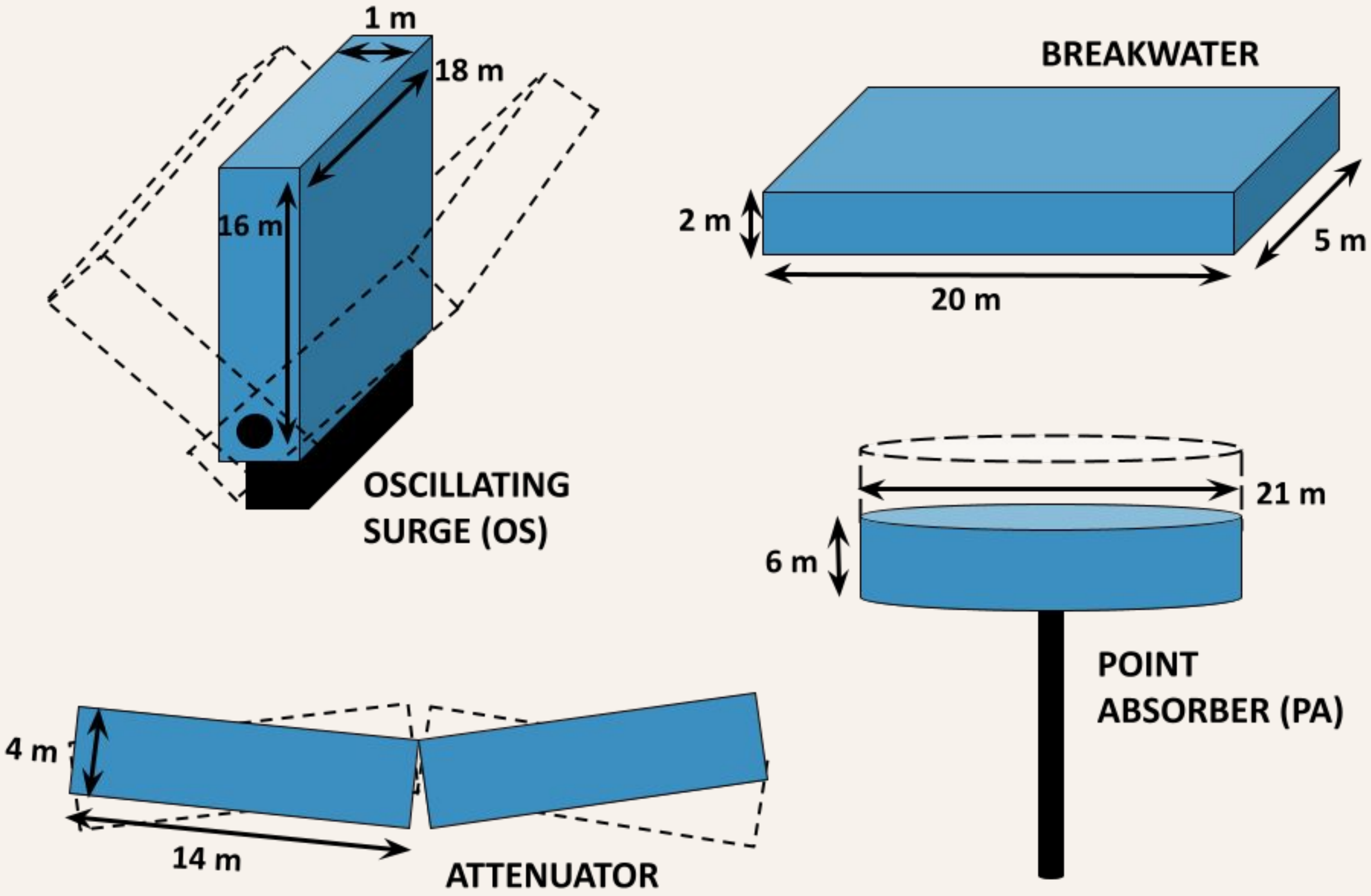
Methodology → Architectures

We analyzed:

- Oscillating surge (OS)
- Heaving point absorber (PA)
- Attenuator
- Breakwater



Individual WECs were sized such that they are **rated for the same power production** (within 5%) at the frequency of interest (1.25 rad/s)

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Methodology → Architectures

Each architecture is modeled in **Capytaine**[21], an open-source boundary element method (BEM) solver

- used to find **hydrodynamic coefficients, incident** (η_{inc})**, diffracted** (η_{diff})**, and radiated** (η_{rad}) **wave elevations**

$$\eta_{tot} = \eta_{inc} + \eta_{diff} + \sum X_i \eta_{rad,i}$$ [21]

i: degree of freedom
*all values are complex

We still need the complex body motion (X_i) to obtain the correct radiated wave elevation

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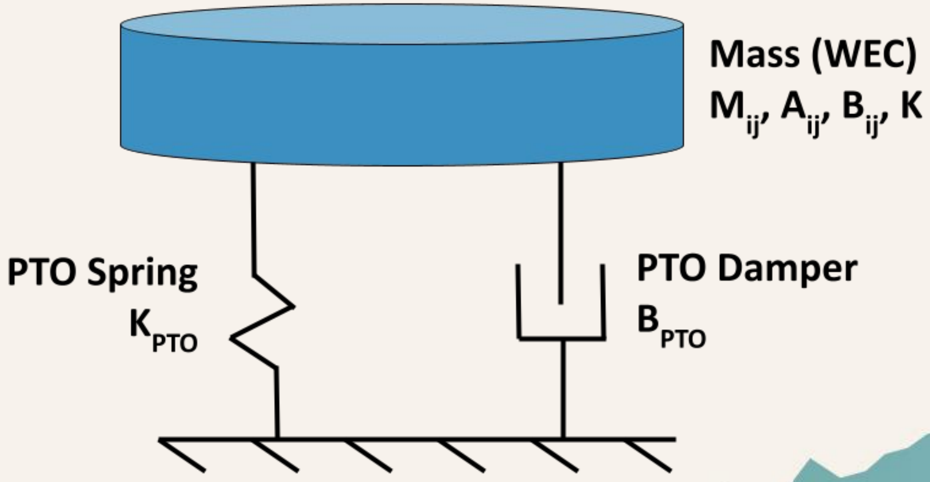
[21] Ancellin, Dias, 2019

Methodology → Architectures

We use the hydrodynamic coefficients (M_{ij},A_{ij},B_{ij},K) to determine body motion

Additionally, we model controllers as **dampers and as spring-dampers** (reactive) for each architecture. These will alter body motion (X_i) to resonate with the wave frequency:

$$\frac{X_i}{A} = \frac{F_{ex}}{-\omega^2(M_{ii} + A_{ij}) - i\omega(B_{ij} + B_{PTO}) + K + K_{PTO}}$$



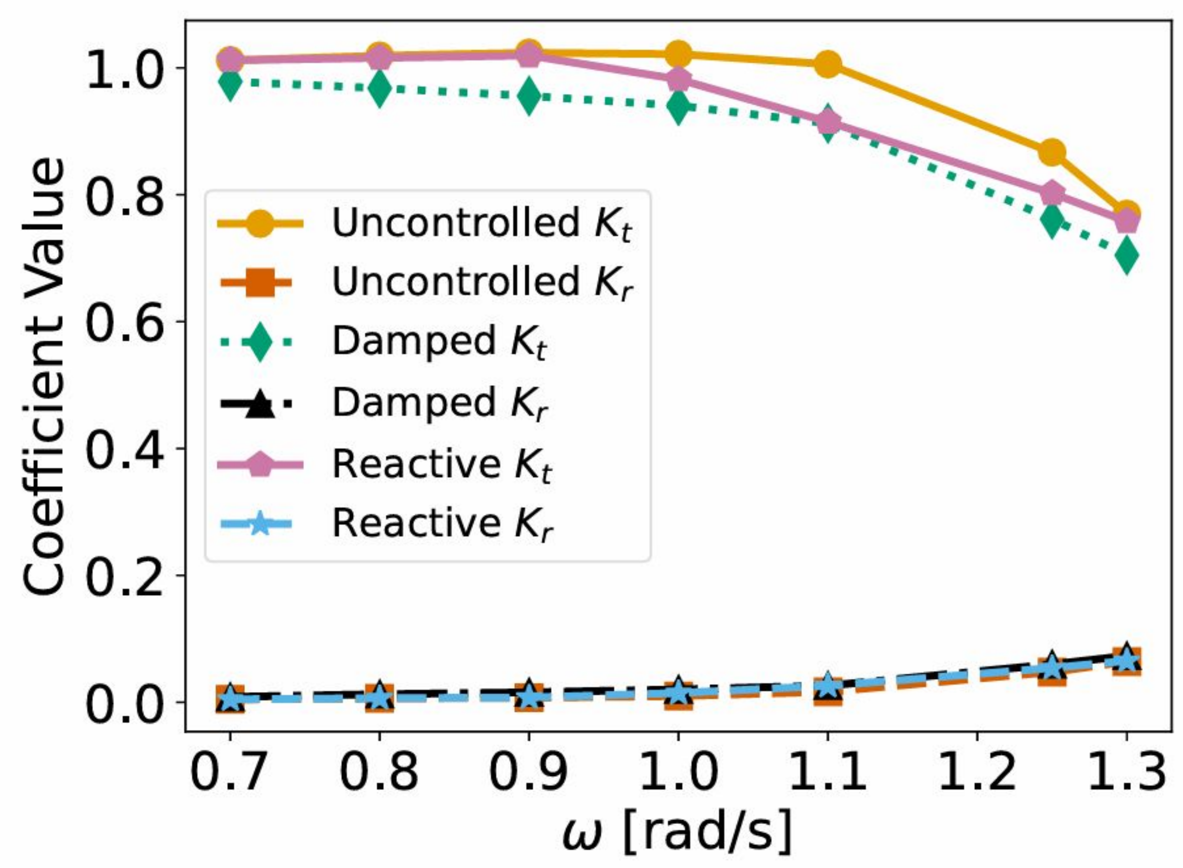
F_{ex}: excitation force
A: wave amplitude
X: complex body motion
M_{ii},A_{ij},B_{ij},K: hydro coeffs

Methodology → Architectures

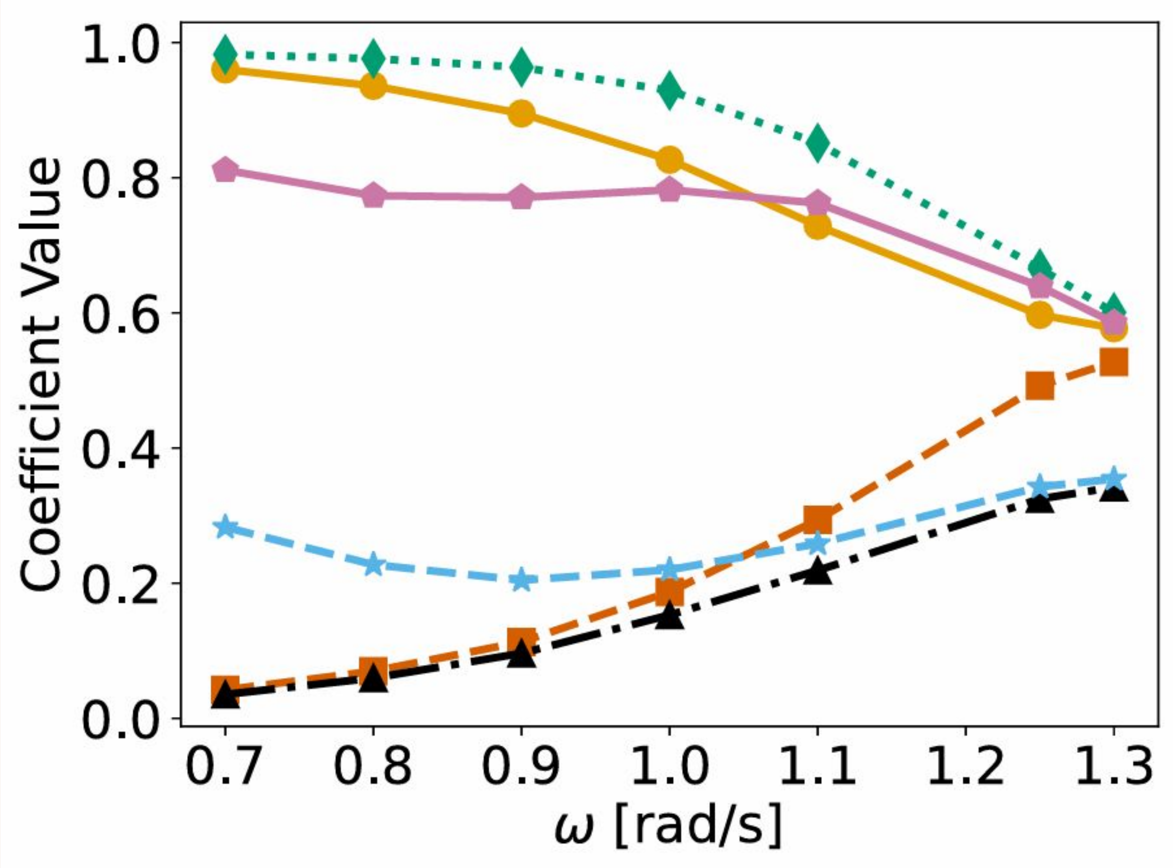
How do different WEC architectures perform in this metric?

- We chose **3 WEC architectures** and 1 breakwater design
- We determine the total **wave elevation**
- We use a **simple control model** and find **complex body motion**

Point Absorber



Oscillating Surge



Results → Single

1. The coefficient **trendline with respect to frequency remains similar** regardless of control scheme
2. Both **perform better at higher frequencies**, with the OSWEC still performing well at low frequencies

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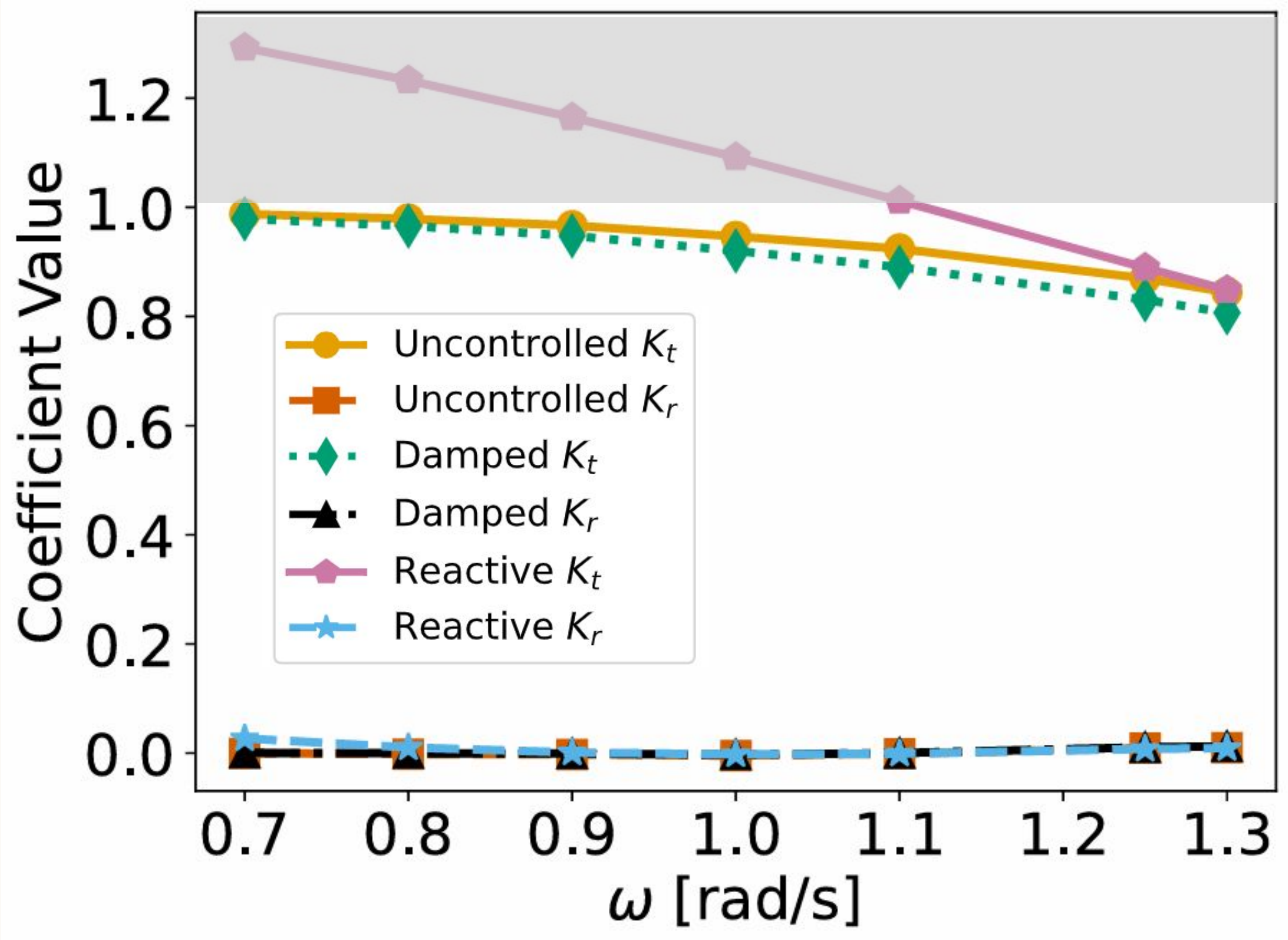
Results → Single

The **attenuator violates energy balance** at <1.2 rad/s when **reactively controlled**

- violating linear potential flow assumption of small body amplitude



Attenuator

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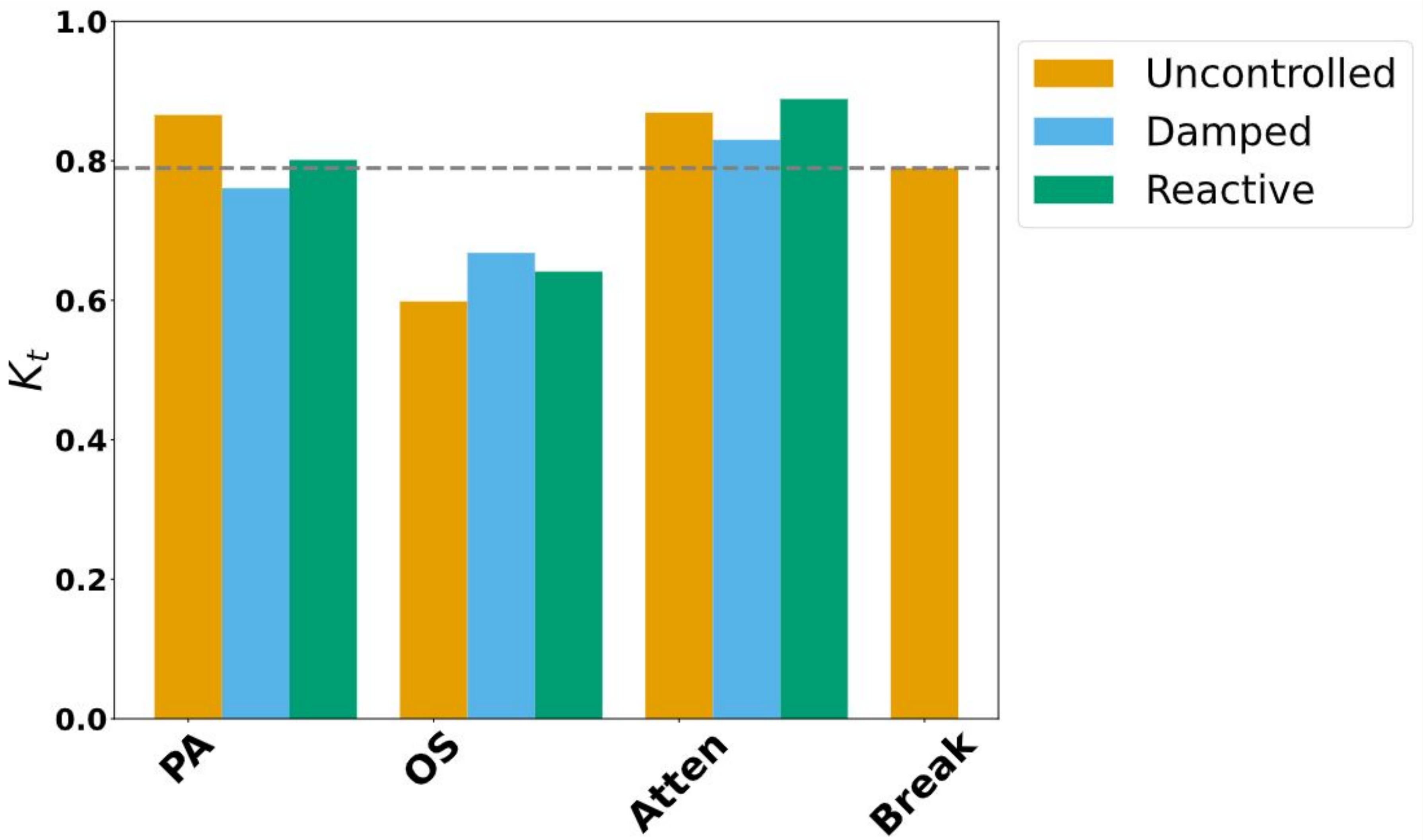
The **OSWEC outperforms** all other architectures

The attenuator cannot outperform the breakwater

Controls significantly alter PA and OS performance (for better and for worse, respectively)



Results → Single

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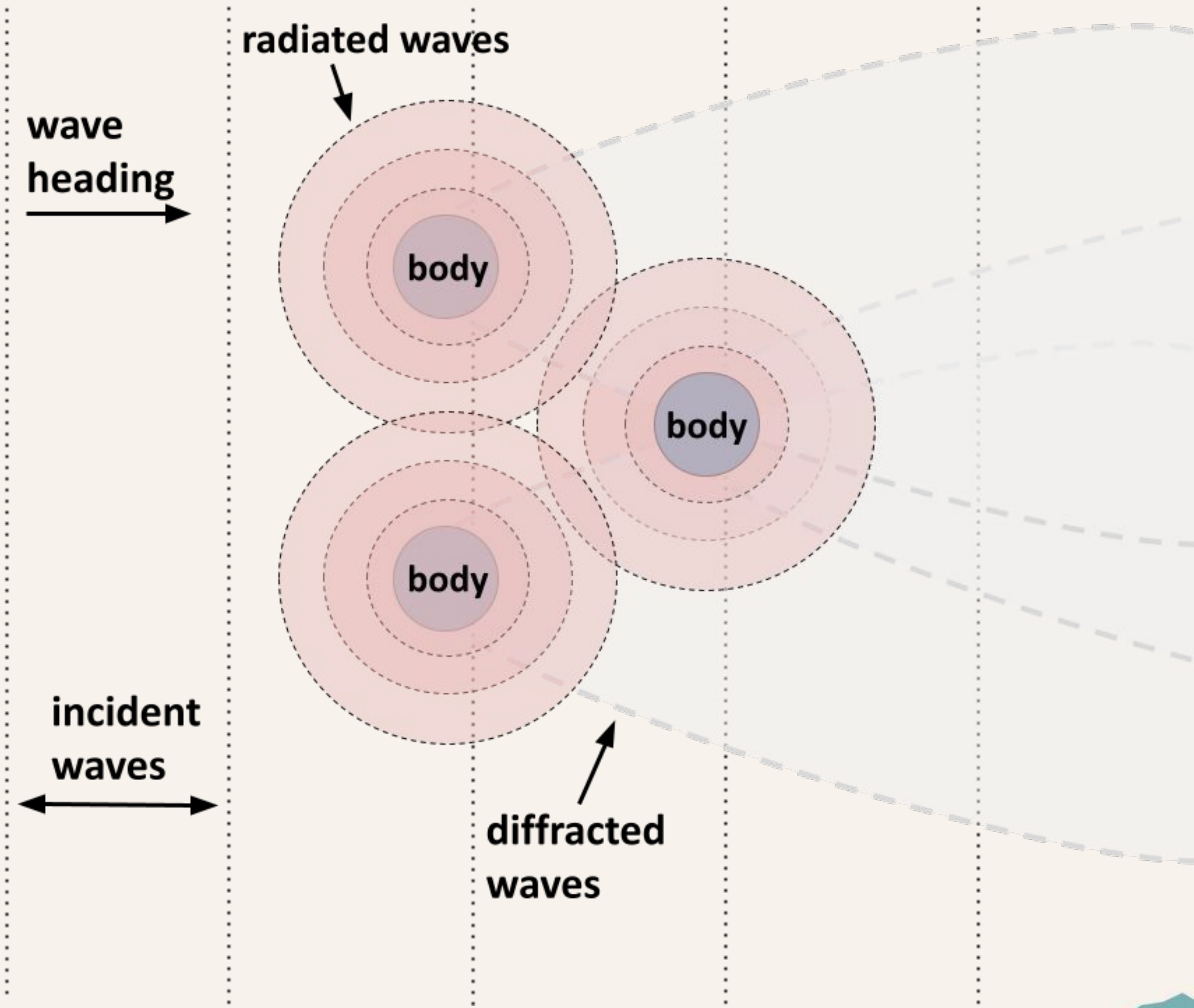
Methodology → Arrays

Oscillating bodies can interact in ways that are constructive or destructive to power production[22,23]

- does this correspond to their wave sheltering performance?



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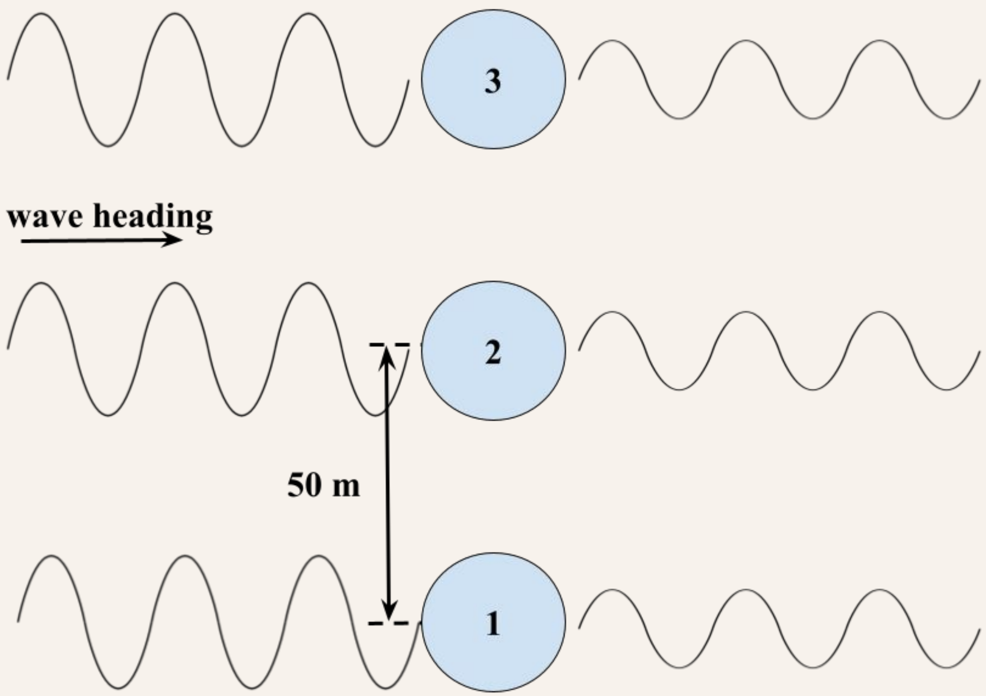
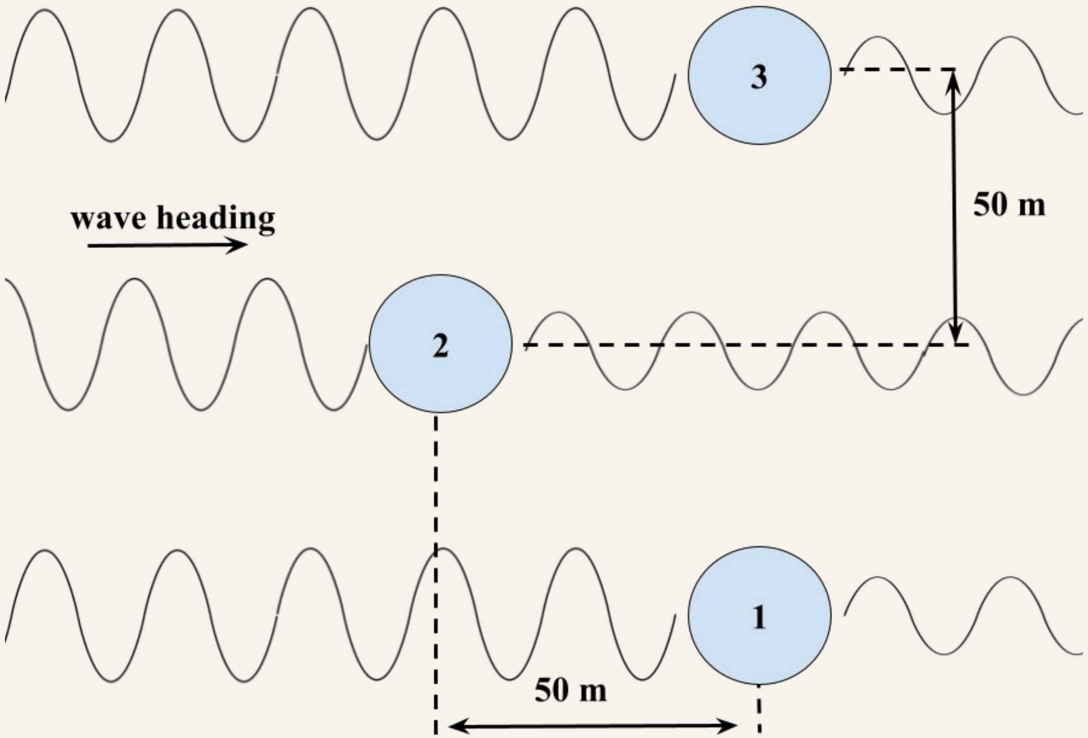
[22] Babarit 2013, [23] Balitsky 2019

Methodology → Arrays

We model two arbitrary, non-optimized array configurations



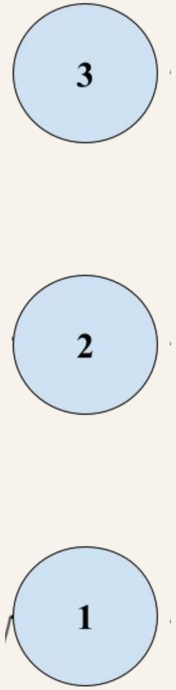
Regular

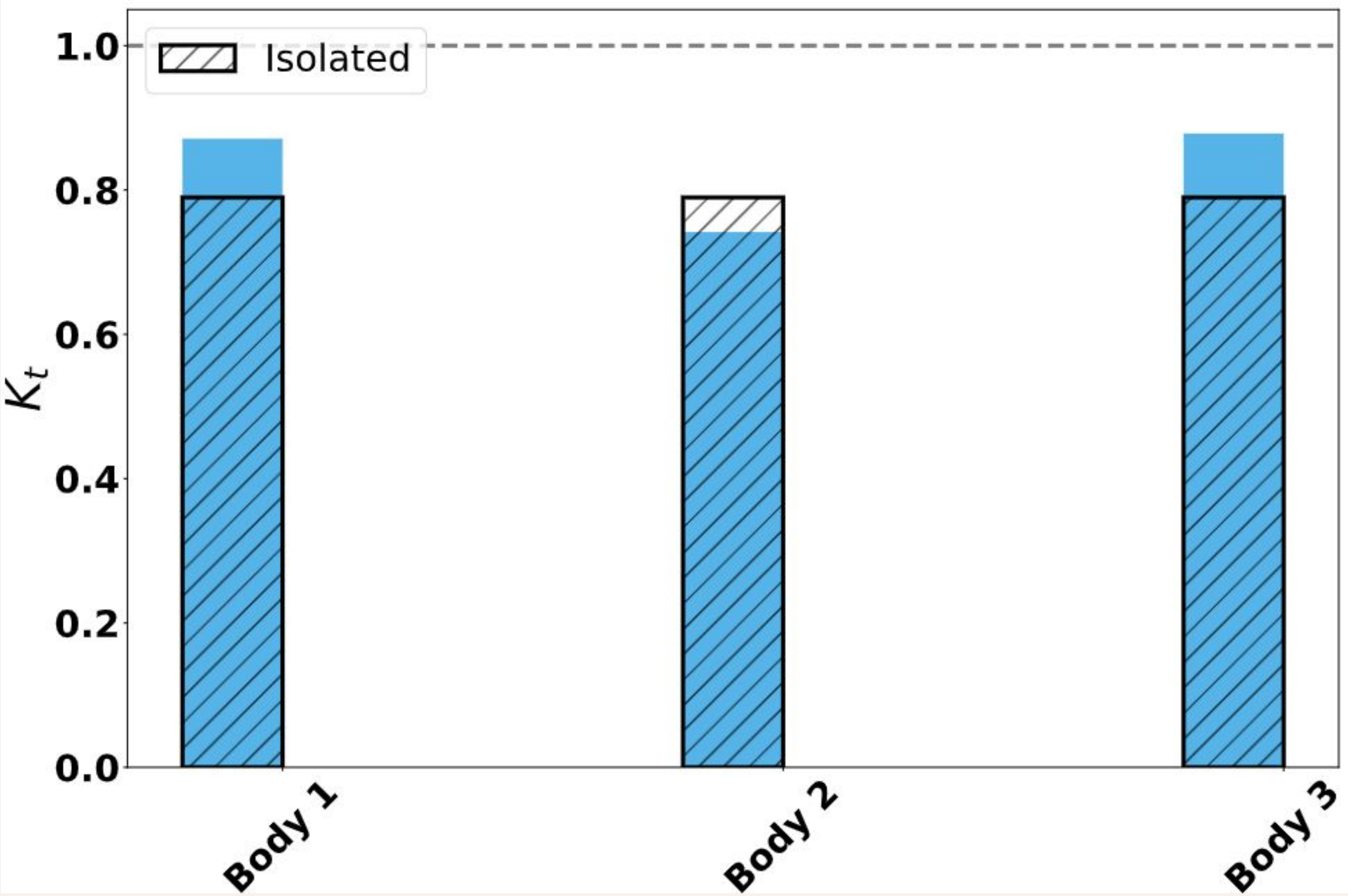


Staggered

Breakwater

The sheltering effect is **concentrated in the center,** with the periphery experiencing less wave sheltering





*at a frequency of 1.25 rad/s

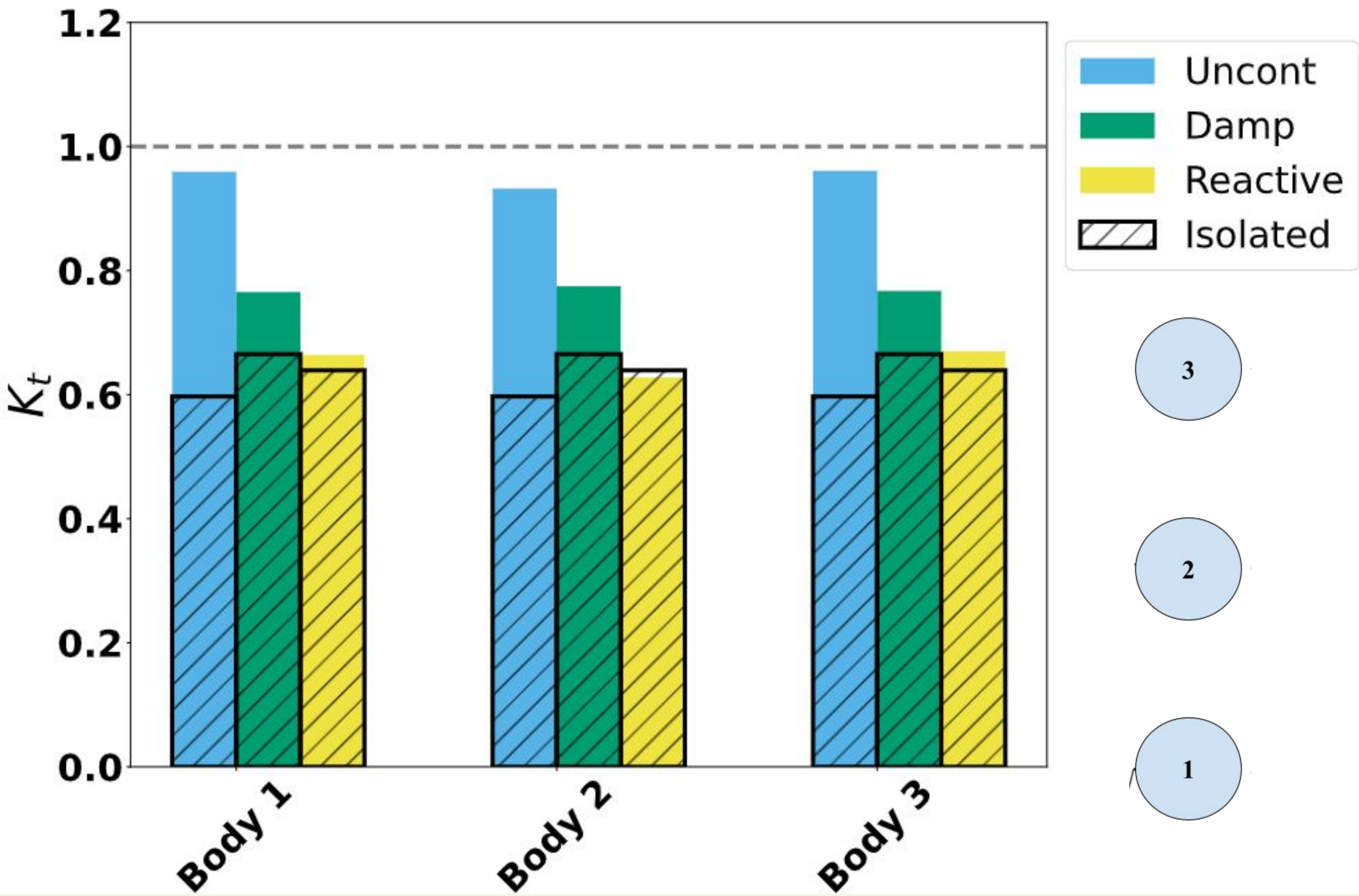
Results → Array (Regular)

Results ⟶ Array (Regular)

OSWEC

We see modeling the body in isolation is **underpredicting wave transmission** for the uncontrolled and damped cases

There is **little change** when the bodies are reactively controlled



*at a frequency of 1.25 rad/s

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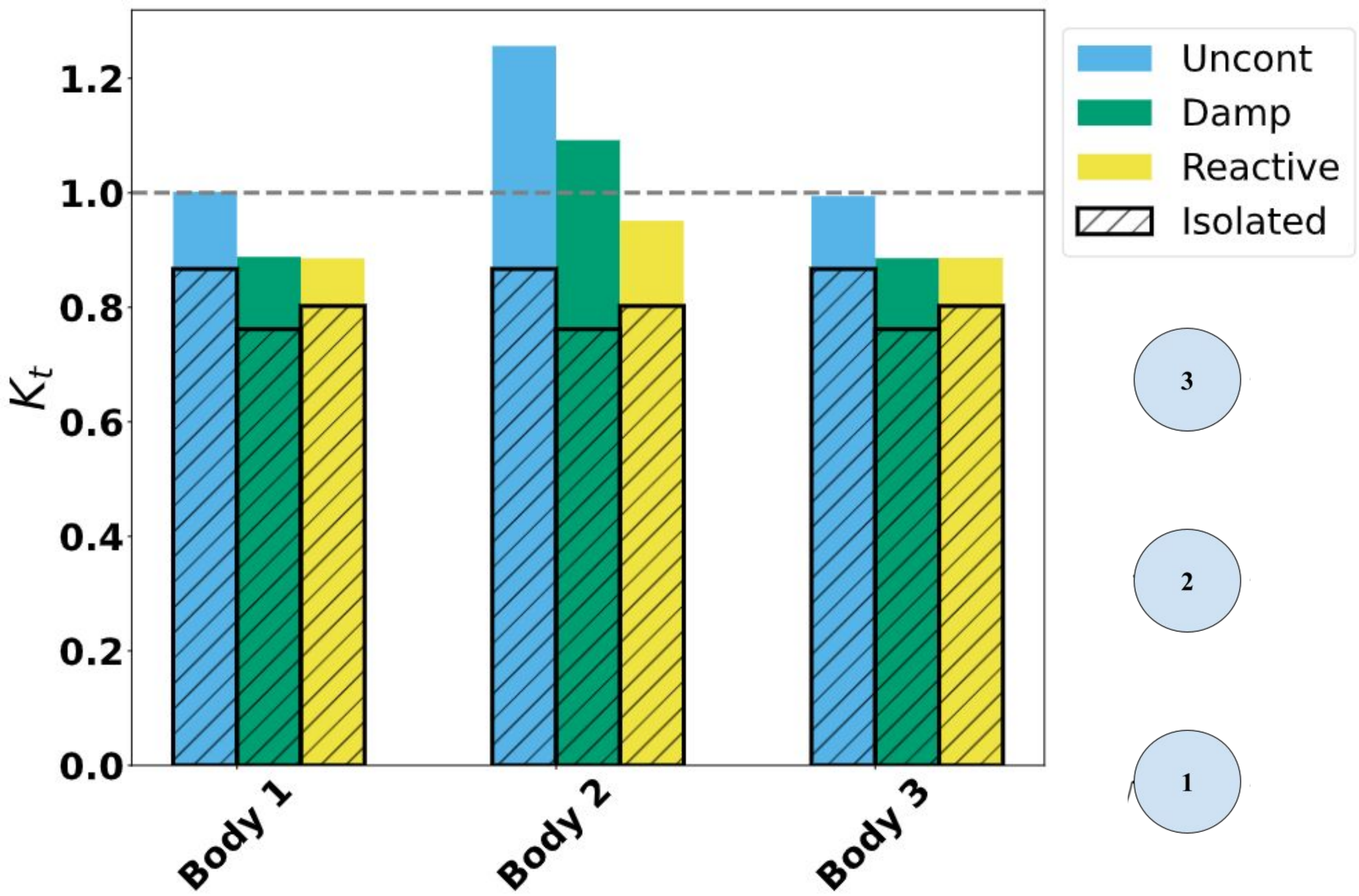
Results ⟶ Array (Regular)

Point Absorber

We see the **wave sheltering of Body 2 negated** by interactions of Bodies 1 and 3 in the damped control case.



*at a frequency of 1.25 rad/s

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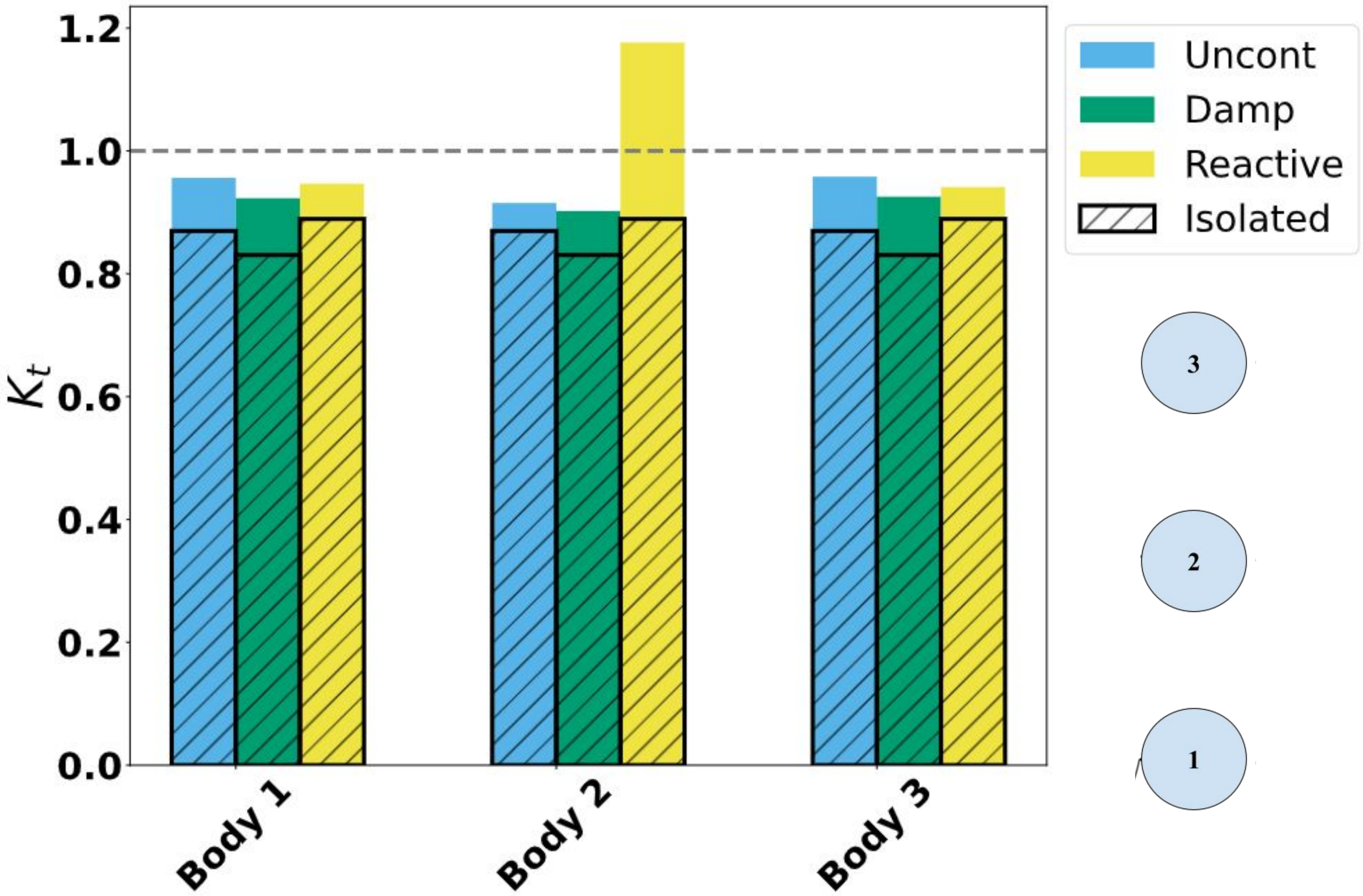
Results ⟶ Array (Regular)

Attenuator

We see a **slight underprediction** and again energy balance violation with reactive control



*at a frequency of 1.25 rad/s

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Conclusions

1. We defined WEC **wave sheltering capabilities by their fluid-structure interactions** (K_t and K_r)

2. We determined the **OSWEC architecture** had the lowest wave transmission across frequencies and the **breakwater typically outperforms the PA and attenuator**

3. We saw that wave sheltering performance can be **affected by array interactions,** but the extent to which this is relevant in the far field needs further investigation

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Thank You!
Questions?

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GitHub (to be released):
https://github.com/symbiotic-engineering/transmission-reflection

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References

[1] Sun, C., Jahangiri, V., 2019. Fatigue damage mitigation of offshore wind turbines under real wind and wave conditions. Engineering Structures 178, 472–483. doi:https://doi.org/10.1016/j.engstruct.2018.10.053.
[2] Häfele, J., Hübler, C., Gebhardt, C.G., Rolfes, R., 2018. A comprehensive fatigue load set reduction study for offshore wind turbines with jacket substructures. Renewable Energy 118, 99–112. doi:https://doi.org/10.1016/j.renene.2017.10.097.
[3] U.S. Geological Survey, "Factors that can affect coastal cliff erosion," U.S. Geological Survey, 2023. [Online]. Available: https://www.usgs.gov/media/images/factors-can-affect-coastal-cliff-erosion. [Accessed: Jul. 30, 2024].
[4] Flanagan, T., Wengrove, M., Robertson, B., 2022. Coupled wave energy converter and nearshore wave propagation models for coastal impact assessments. J. Mar. Sci. Eng. 10, 370. URL: https://doi.org/10.3390/jmse10030370, doi:10.3390/jmse10030370. submission received: 7 January 2022 / Revised: 25 February 2022 / Accepted: 1 March 2022 / Published: 5 March 2022.
[5] Chang, G., Ruehl, K., Jones, C., Roberts, J., Chartrand, C., 2016. Numerical modeling of the effects of wave energy converter characteristics on nearshore wave conditions. Renewable Energy 89, 636–648. doi:https://doi.org/10.1016/j.renene.2015.12.048.
[6] Contardo, S., Hoeke, R., Hemer, M., Symonds, G., McInnes, K., O'Grady, J., 2018. In situ observations and simulations of coastal wave field transformation by wave energy converters. Coastal Engineering 140, 175–188. doi:https://doi.org/10.1016/j.coastaleng.2018.07.008.
[7] Rusu, E., Guedes Soares, C., 2013. Coastal impact induced by a pelamis wave farm operating in the portuguese nearshore. Renewable Energy 58, 34–49. doi:https://doi.org/10.1016/j.renene.2013.03.001.
[8] Silva, D., Rusu, E., Guedes Soares, C., 2018. The effect of a wave energy farm protecting an aquaculture installation. Energies 11, 2109.submission received: 7 July 2018 / Revised: 5 August 2018 / Accepted: 6 August 2018 / Published: 13 August 2018
[9] Astariz, S., Perez-Collazo, C., Abanades, J., Iglesias, G., 2015. Co-located wind-wave farm synergies (operation maintenance): A case study. Energy Conversion and Management 91, 63–75. doi:https://doi.org/10.1016/j.enconman.2014.11.060.
[10] Clark, C.E., Paredes, G.M., 2018. Effects of co-located floating wind-wave systems on fatigue damage of floating offshore wind turbine mooring cables, in: Proceedings of the ASME 2018 1st International Offshore Wind Technical Conference, p. V001T01A024. doi:10.1115/IOWTC2018-1077.
[11] Clark, C.E., Velarde, J., Sønderkær Nielsen, J., 2018. Fatigue load reductions in offshore wind turbine monopile foundations in co-located wind-wave arrays, in: Proceedings of the ASME 2018 1st International Offshore Wind Technical Conference, p. V001T01A037. doi:10.1115/IOWTC2018-1024.
[12] NREL, "Coastal Structure-Integrated Wave Energy Converters," National Renewable Energy Laboratory, 2023. [Online]. Available: https://www.nrel.gov/water/coastal-structure-integrated-wave-energy-converters.html. [Accessed: Aug. 1, 2024].
[13] Venugopal, V., Nemalidinne, R., Vögler, A., 2017. Numerical modelling of wave energy resources and assessment of wave energy extraction by large scale wave farms. Ocean Coastal Management 147, 37–48. doi:https://doi.org/10.1016/j.ocecoaman.2017.03.012. tools for managing the development of the wave and tidal energy resource (TeraWatt).
[14] Zou, S., Robertson, B., Roach, A., Mundon, T., Rosenberg, B., Penalba, M., 2024. Wave energy converter arrays: A methodology to assess performance considering the disturbed wave field. Renewable Energy 229, 120719. doi:https://doi.org/10.1016/j.renene.2024.120719.
[15] Seelig, W.N., 1980. Two-Dimensional Tests of Wave Transmission and Reflection Characteristics of Laboratory Breakwaters. Technical Report NO. 80-1. Q TECHNICAL REPORT.
[16] Carballo, R., Iglesias, G., 2013. Wave farm impact based on realistic wave-wec interaction. Energy 51, 216–229. doi:https://doi.org/10.1016/j.energy.2012.12.040
[17] Atan, R., Finnegan, W., Nash, S., Goggins, J., 2019. The effect of arrays of wave energy converters on the nearshore wave climate. Ocean Engineering 172, 373–384. doi:https://doi.org/10.1016/j.oceaneng.2018.11.043.
[18] Bao, L., Wang, Y., Jiang, C., Chen, J., Li, H., Wang, S., 2022. Research on wave and energy reduction performance of floating breakwater based on s-shaped runner. Energies 15, 5148. doi:10.3390/en15145148. this article belongs to the Special Issue Electrical Systems for Marine Renewable Energy Applications.
[19] Seelig, W.N., Ahrens, J.P., 1981. Estimation of Wave Reflection and Energy Dissipation Coefficients for Beaches, Revetments, and Breakwaters. Technical Paper 81-1. U.S. Army Corps of Engineers, Coastal Engineering Research Center. Approved for public release; distribution unlimited
[20] Falnes, J., Kurniawan, A., 2020. Ocean Waves and Oscillating Systems: Linear Interactions Including Wave-Energy Extraction. Cambridge Ocean Technology Series. 2 ed., Cambridge University Press
[21] Ancellin, M., Dias, F., 2019. Capytaine: a Python-based linear potential flow solver. Journal of Open Source Software 4, 1341. URL: https://doi.org/10.21105%2Fjoss.01341, doi:10.21105/joss.01341.
[22] Babarit, A., 2013. On the park effect in arrays of oscillating wave energy converters. Renewable Energy 58, 68–78. doi:https://doi.org/10.1016/j.renene.2013.03.008.
[23] Balitsky, Philip, 2019. A numerical investigation of the array effects of wave energy converters with a realistic power take-off system utilizing a coupled model suite. Ph.D. thesis. Ghent University.