CASHEW: CArbon Sequestration Harnessing Energy from Waves

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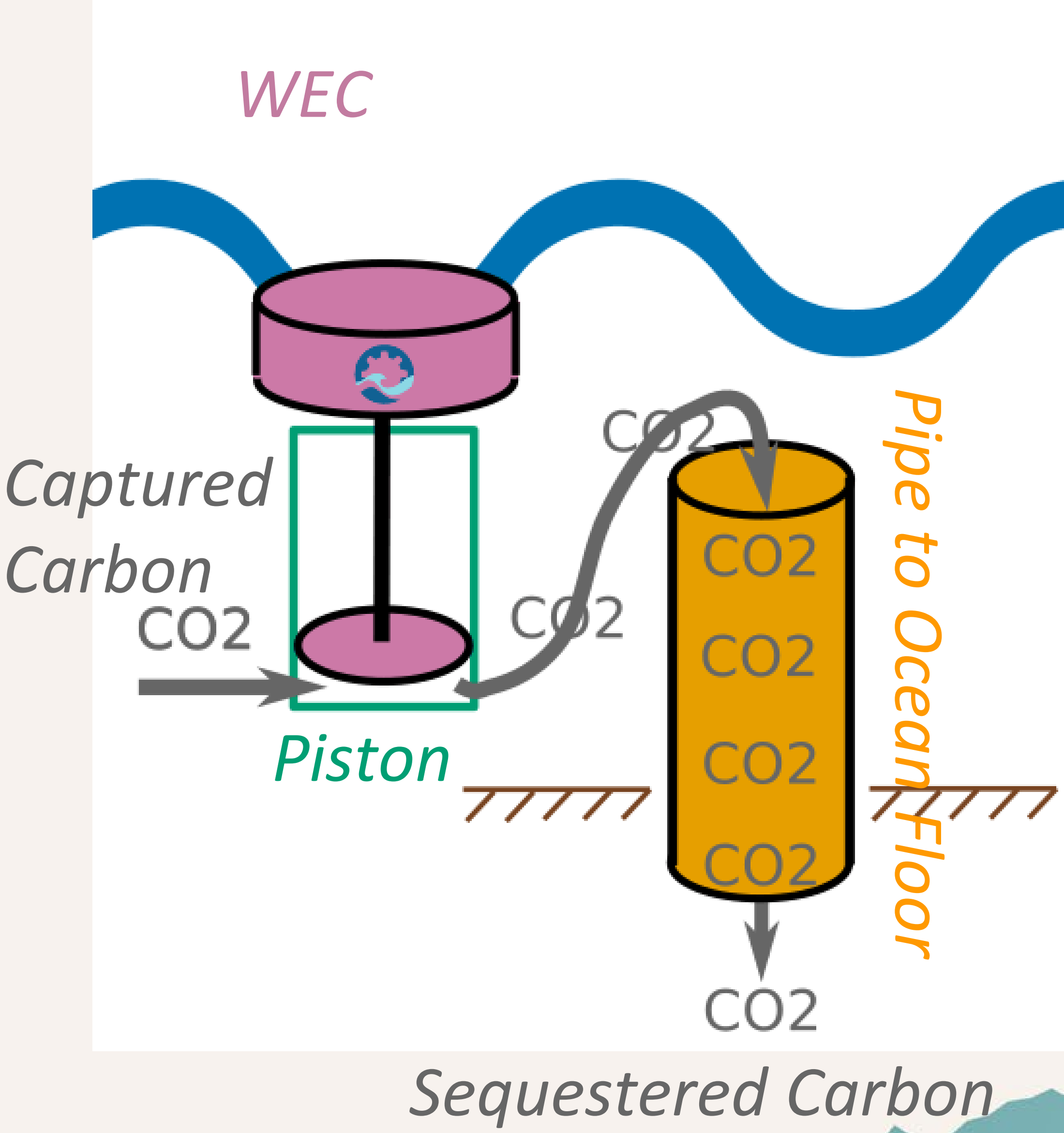
Agenda

- Motivation
    - Carbon Sequestration
    - Fit for WECs
- Requirements
- Modeling
    - Analytical
    - Numerical
- Conceptual System Design
- Location
- Economic Model
- Future Work

Motivation

- Marine Carbon Storage (mCS)
  - Can hold carbon for 1,000 - 100,000 years
  - CO_2 density changes
- Sequestration ≠ Carbon Capture
- Power suitability
  - Sequestration requires mechanical energy
  - WECs capture mechanical energy
  - Builds on wave driven desalination



Requirements

Requirement	Derived Assumption
Sequester 1 Gt/yr at scale	31 arrays of 100 WECs, 0.32 Mt/yr each
Sufficient pressure and flow	Fracture 200 m below seafloor
Gravitational trapping	Liquid CO_2, depth >2700 m
Economic viability	$148/t long-term, better than offshore wind short-term
WEC feasibility	10 MN max force, 5 m/s max speed, obey radiation limit

Analytical Modeling of Compressible Flow

- Pressure at seafloor: frack the seabed to increase permeability

$$P_{frack} \approx 700(z_{injection} - z_{seafloor})^{1.5}$$

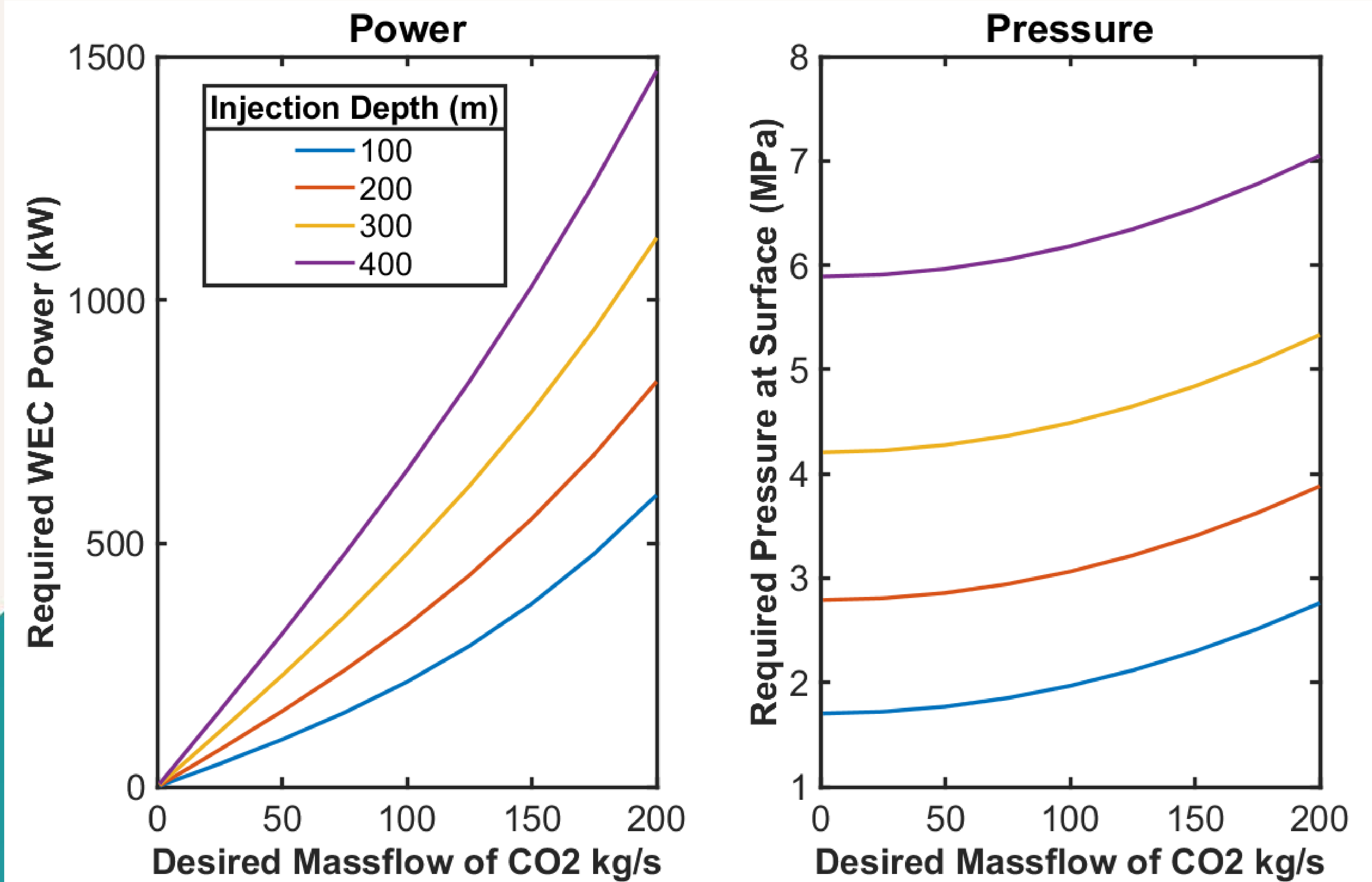
- Pressure at sea surface: iterate up using gravity and pipe loss

$$P_{CO_2}(z=0) = P_{CO_2}(z_{injection}) + \sum_i \left(\frac{1}{2}\rho_{CO_2,i} v_i^2 f \frac{\Delta z_i}{D} - \rho_{CO_2,i} g \Delta z_i \right)$$

- Power: pressure times volume flow

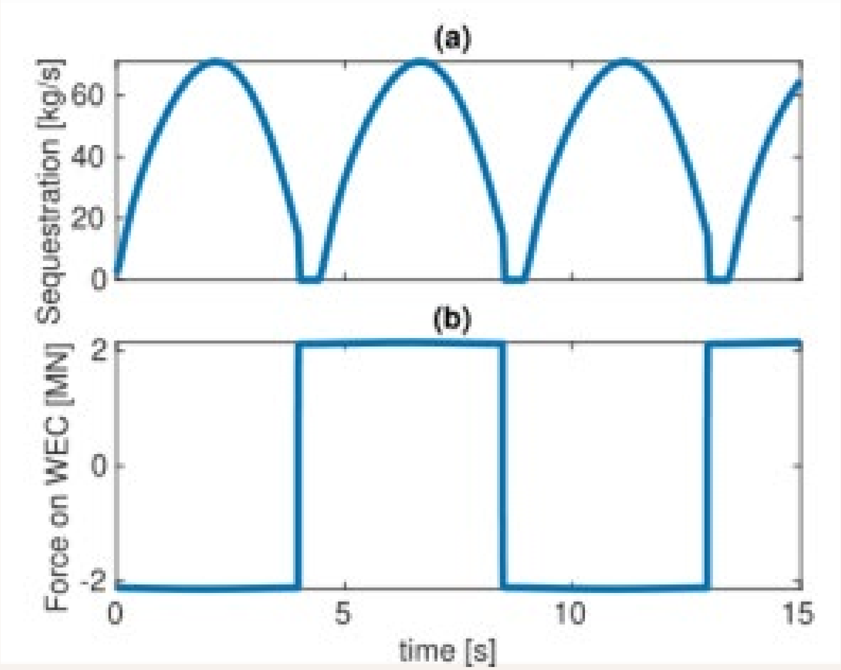
$$\dot{W} = F_{PTO} v_{PTO} = P_{CO_2}(z=0)\ v(z=0) \frac{\pi}{4} D^2 = P_{CO_2}(z=0) \frac{\dot{m}}{\rho_{CO_2}(z=0)}$$

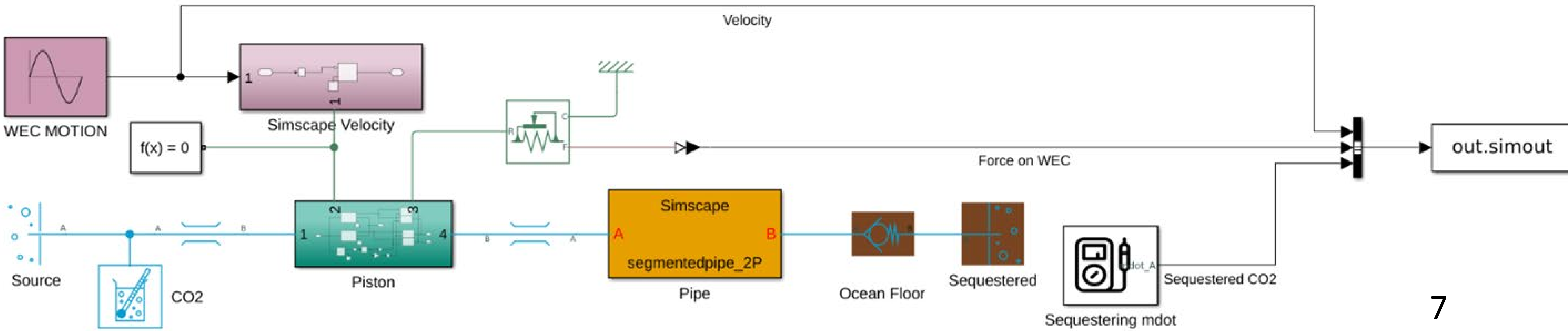
Analytical Modeling Results



Numerical Modeling

- Time domain solver in Simscape
  - Transient dynamics
  - CO_2 compressibility
  - Double acting piston
- Further theoretical proof of concept





System Design

Parameter	Value	Unit
Piston area	0.01	m^2
Pipe inner diameter	0.26	m
Injection depth below seafloor	200	m
Effective pressure at injection depth	2	MPa
Water depth	2700	m
Pressure required at surface	3	MPa
Average massflow CO_2	10, 0.32	kg/s, Mt/yr
Nominal WEC amplitude	1	m
Nominal wave frequency	0.7	rad/s
Average power at nominal conditions	965	kW
Liquid CO2 temperature	0	C

Location

- Available wave energy
- Seawater density (salinity and temperature)
- Seabed geology (basalt sequestration)
- Water depth
- Decommissioned oil rigs
- Nearby carbon capture technology

Economic Model

Levelized cost of carbon ($/ton)

Energy intensity (kWh/ton)

Annual discounted non-energy cost ($/yr)

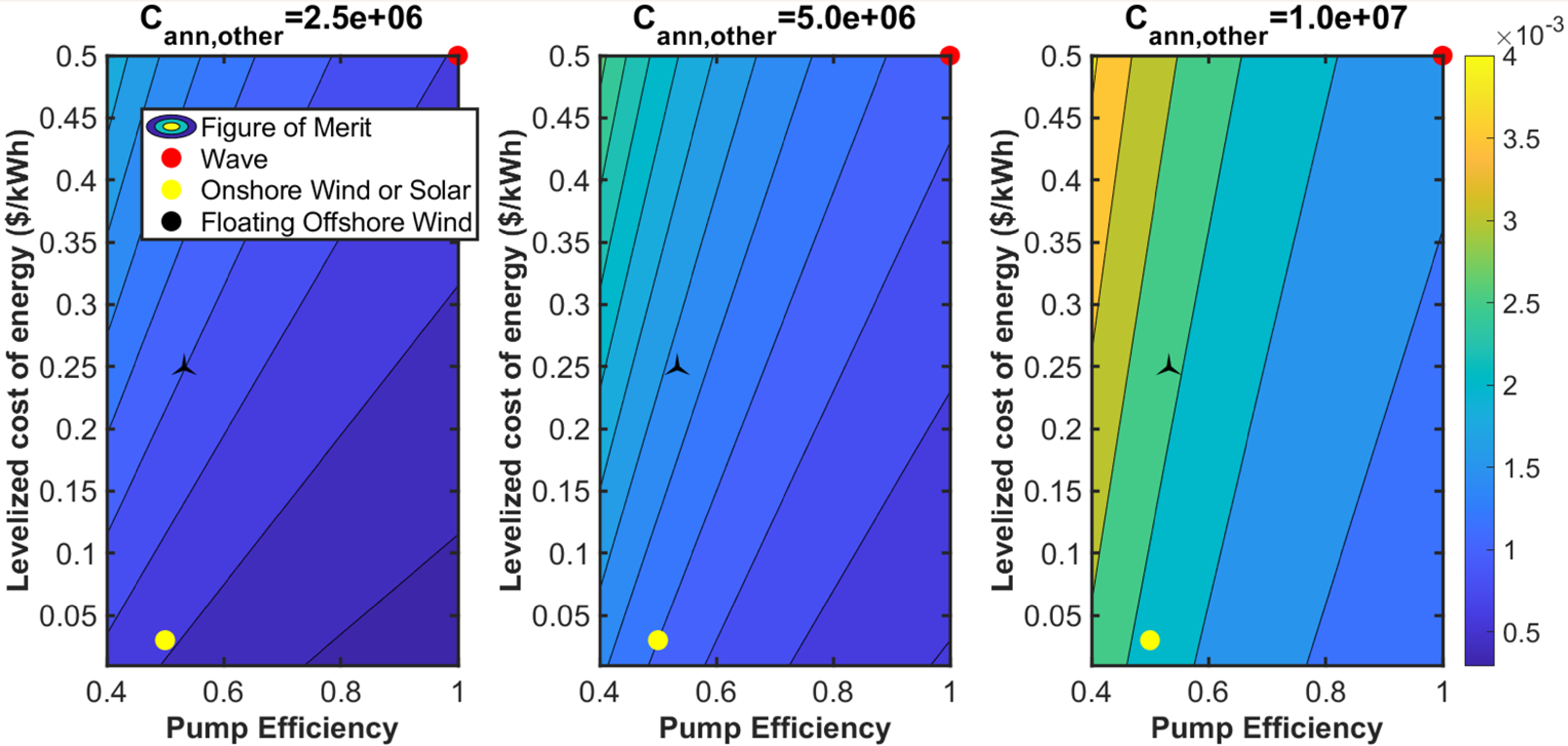
$$LCOC = \frac{EI}{\eta}\left(LCOE + \frac{C_{ann,other}}{AEP}\right)$$

Pump Efficiency (-)

Levelized cost of energy ($/kWh)

Annual energy production (kWh/yr)

Economic Results



Future Work

- Revisit assumptions
- Investigate analytical vs numerical discrepancy
- Real hydrodynamics modeling + impedance matching
- More detailed economic model
- (Possibly) partner to prototype

Model available open-source: https://github.com/symbiotic-engineering/CASHEW

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References

[1] J. Niffenegger, D. Greene, R. Thresher, and M. Lawson, "Mission analysis for marine renewable energy to provide power for marine carbon dioxide removal," Tech. Rep. Report, National Renewable Energy Laboratory, 9 2023.

[2] H. Norton, D. Todd, and C. Crawford, "Storage capacity estimates and site conditions of potential locations for offshore-wind powered carbon dioxide removal and carbon sequestration in ocean basalt,"Carbon Capture Science & Technology, vol. 13, p. 100231, Dec. 2024.

[3] H. Norton, P. Gillessen, and C. Crawford, "Techno-economic assessment of supercritical, cold liquid, and dissolved CO2 injection into sub-seafloor basalt," Carbon Capture Science & Technology, vol. 13, p. 100236, Dec. 2024.

[4] "Captura: Technology." Available at https://capturacorp.com/technology/.

[5] J. S. Levine, J. M. Matter, D. Goldberg, A. Cook, and K. S. Lackner, "Gravitational trapping of carbon dioxide in deep sea sediments: Permeability, buoyancy, and geomechanical analysis," Geophysical Research Letters, vol. 34, no. 24, 2007. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2007GL031560.

[6] P. Davies, "Wave-powered desalination: resource assessment and review of technology," Desalination, vol. 186, pp. 97–109, Dec. 2005.

[7] K. M. Brodersen, E. A. Bywater, A. M. Lanter, H. H. Schennum, K. N. Furia, M. K. Sheth, N. S. Kiefer, B. K. Cafferty, A. K. Rao, J. M. Garcia, and D. M. Warsinger, "Direct-drive ocean wave-powered batch reverse osmosis,"Desalination,vol. 523, p. 115393, Feb. 2022.

[8] Y.-H. Yu and D. Jenne, "Numerical modeling and dynamic analysis of a wave-powered reverse-osmosis system," Journal of Marine Science and Engineering, vol. 6, p. 132, Nov. 2018.

[9] "Methods to determine pore pressure," Jan. 2016. Available at https://petrowiki.spe.org/Methods_to_determine_pore_pressure.

[10] S. Zou, B. Robertson, and S. Yim, "Practical power absorption assessment limits for generic wave energy converters," Ocean Engineering, vol. 277, p. 114303, June 2023.

[11] V. S. Neary, M. Previsic, R. A. Jepsen, M. J. Lawson, Y.-H. Yu, A. E. Copping, A. A. Fontaine, K. C. Hallett, and D. K. Murray, "Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies," Tech. Rep. SAND2014-9040, Sandia National Laboratories, Albuquerque, New Mexico, Mar. 2014.

[12] L. Davis, "Using an offshore platform beyond its expected lifespan | Engineer Live," Aug. 2018.

[13] G. Bacelli, J.-C. Gilloteaux, and J. Ringwood, "A predictive controller for a heaving buoy producing potable water," in European Control Conference, 2009.

[14] B. J. Hopkins, N. Padhye, A. Greenlee, J. Torres, L. Thomas, D. M. Ljubicic, M. P. Kassner, and A. H. Slocum, "Damping pressure pulsations in a wave-powered desalination system," Journal of Energy Resources Technology, vol. 136, Apr. 2014.

[15] "Primre marine energy projects database: Devices." Available at https://openei.org/wiki/PRIMRE/Databases/Projects_Database/Devices.

[16] "Oneka." Available at https://www.onekawater.com/.