Low-Pressure Circuit Design for Hydraulic Power Take-Offs in Wave-Powered Reverse Osmosis

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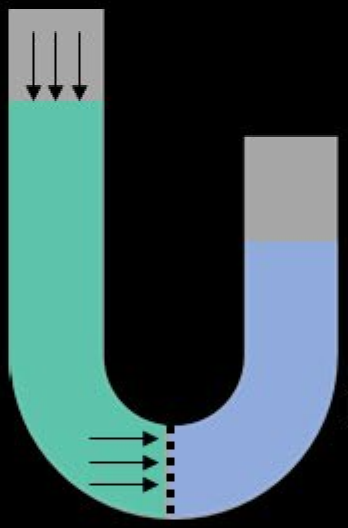
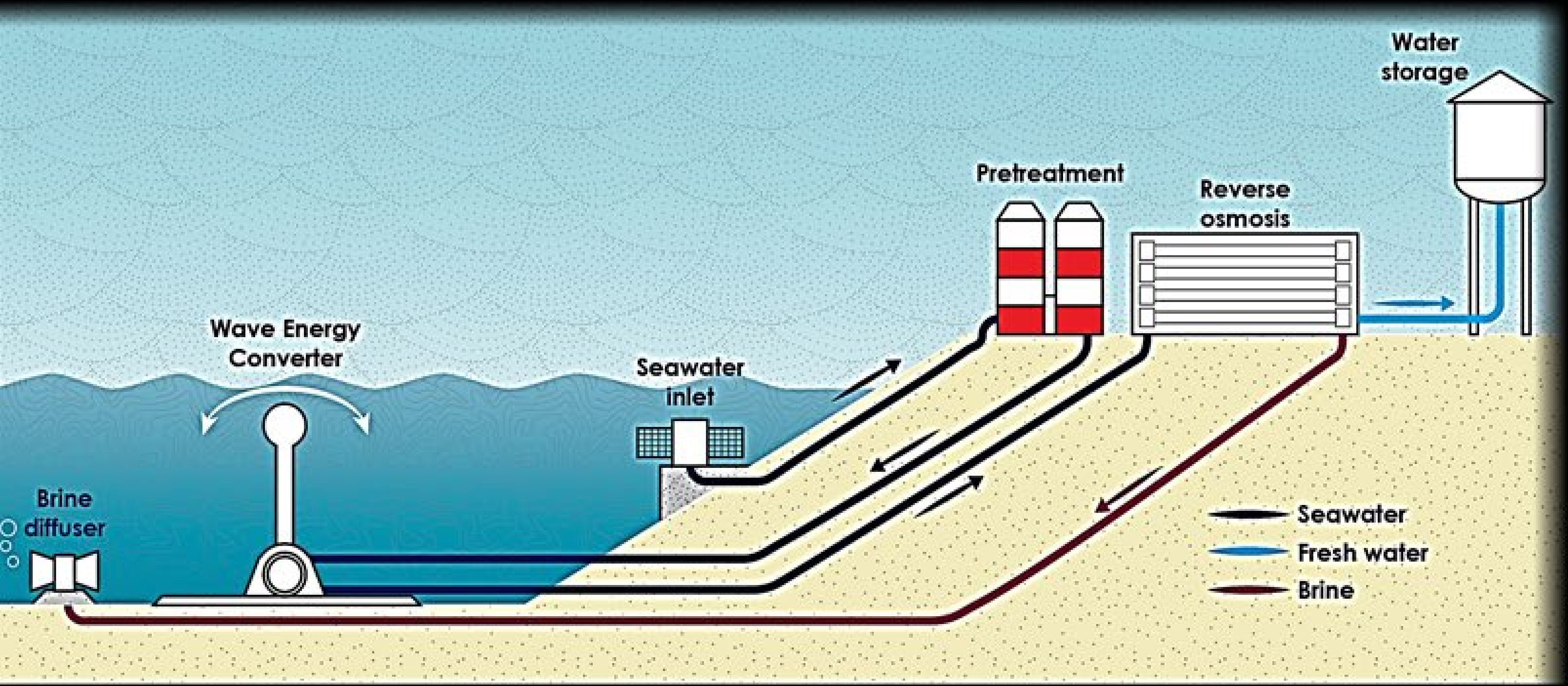
Fresh Water From Waves

Wave Energy

Applied Pressure

Reverse Osmosis





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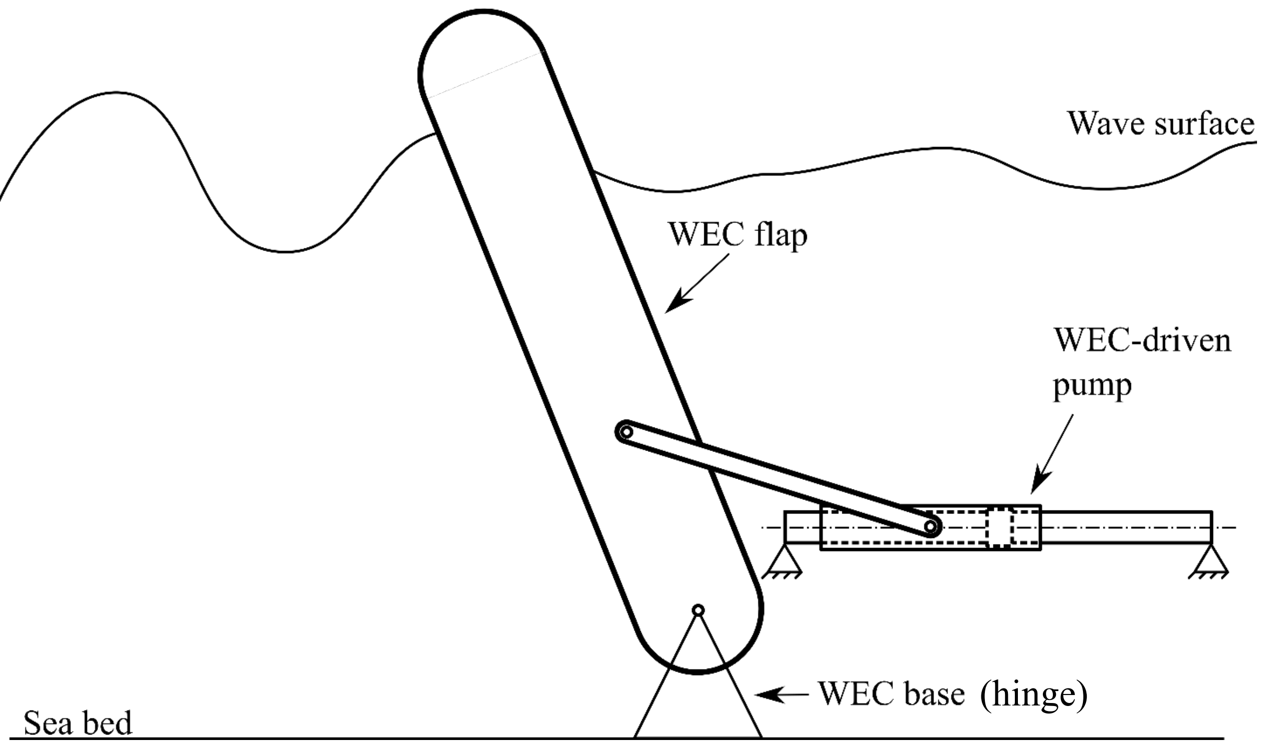
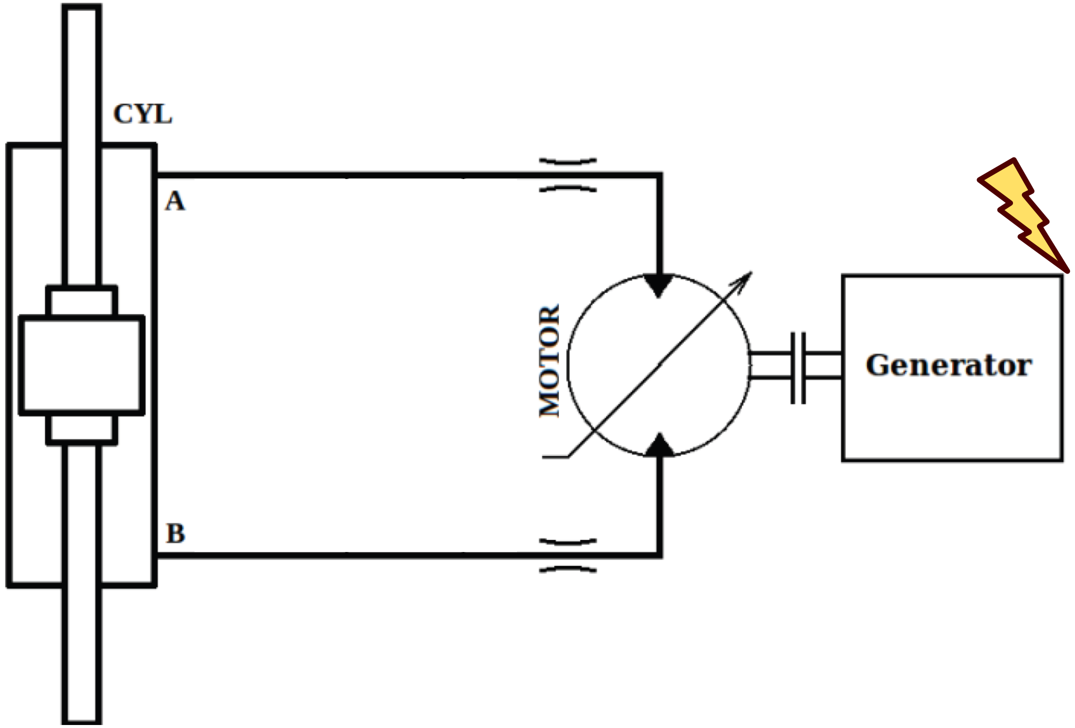
Waves to Electricity

Wave Energy Converter (WEC)



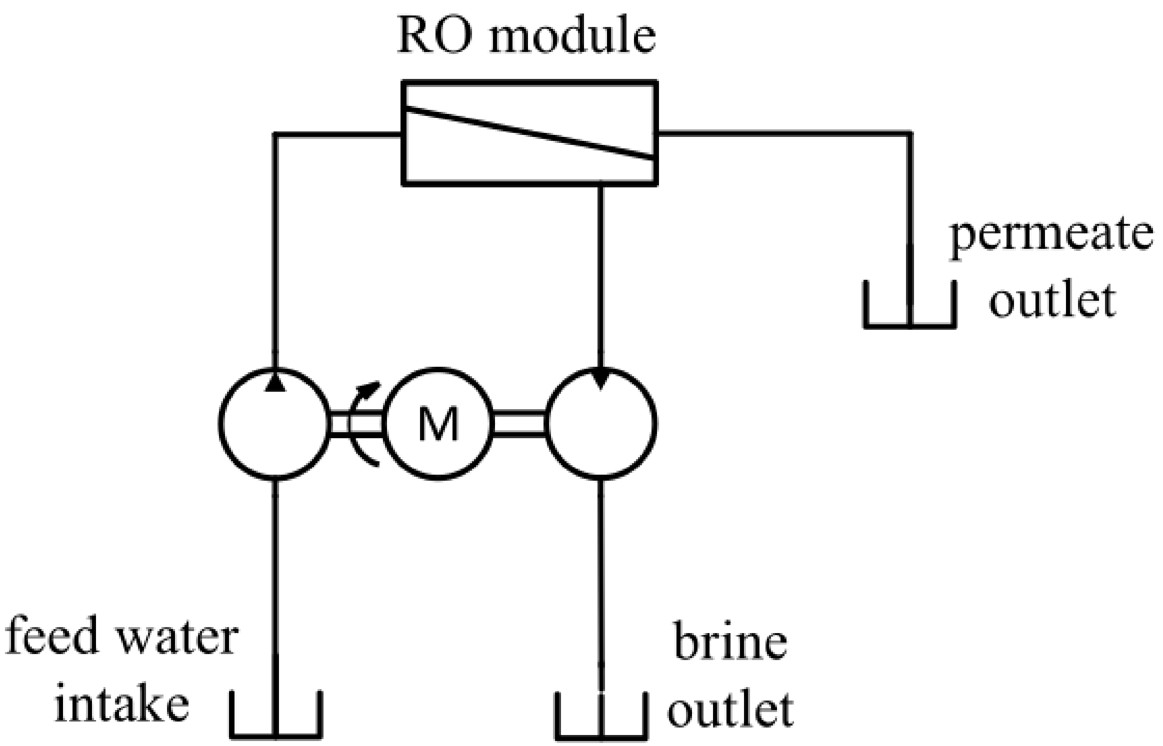
Power Take-Off (PTO)



(Right) Adapted from: Costello et al., 2011, "Comparison of two alternative hydraulic PTO concepts for wave energy conversion," Proceedings of the 9th European wave and tidal energy conference (EWTEC).

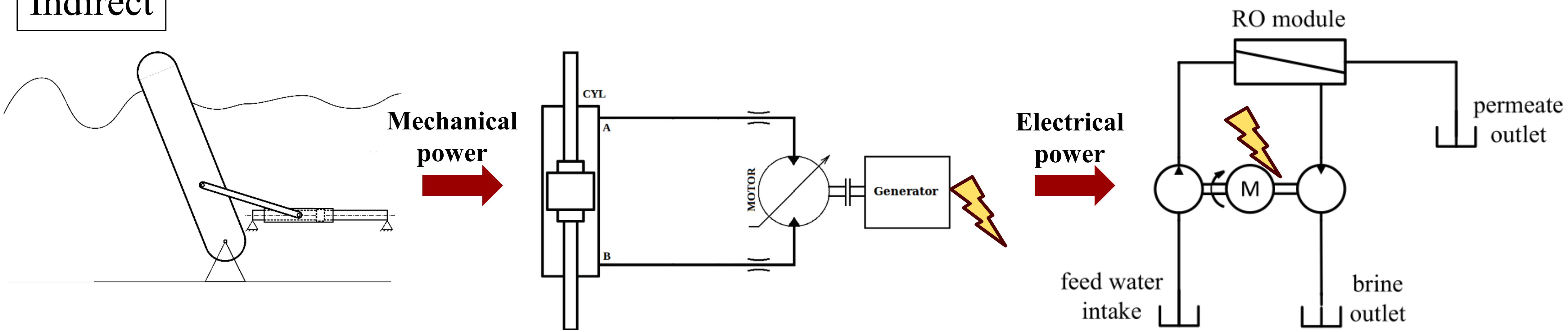
Conventional Reverse Osmosis (RO)

- Constant operating pressure and flow rate
- Requires slow start-up
  - 70 kPa/s ramp in pressure
- Powered by electric power or IC engine
- Energy recovered from high-pressure brine stream

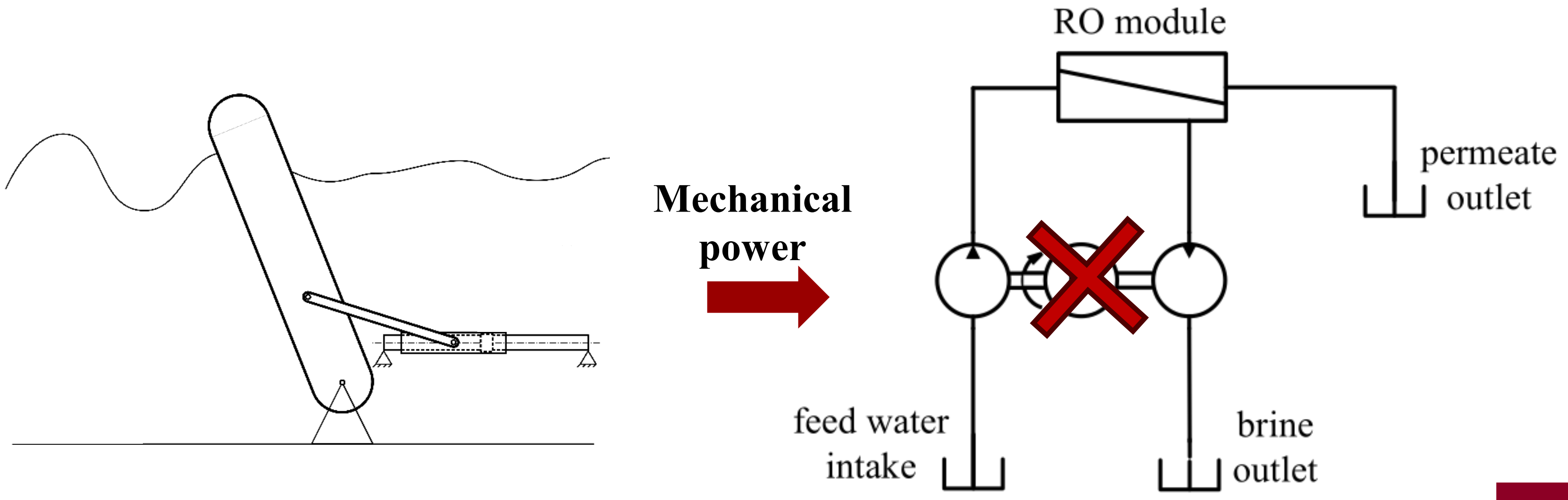


Approaches to Wave-Powered RO

Indirect



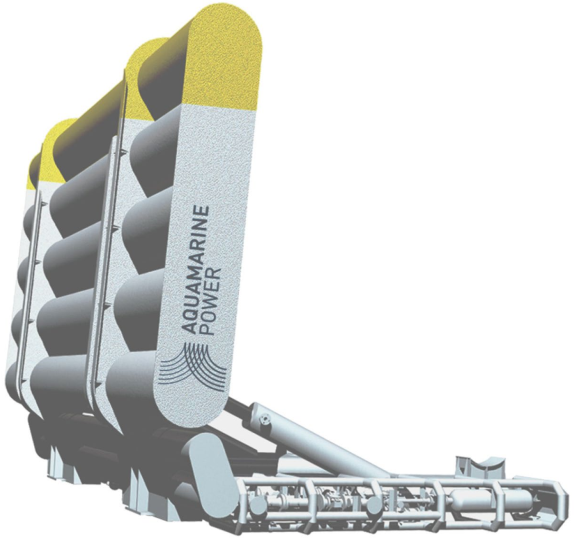
Direct

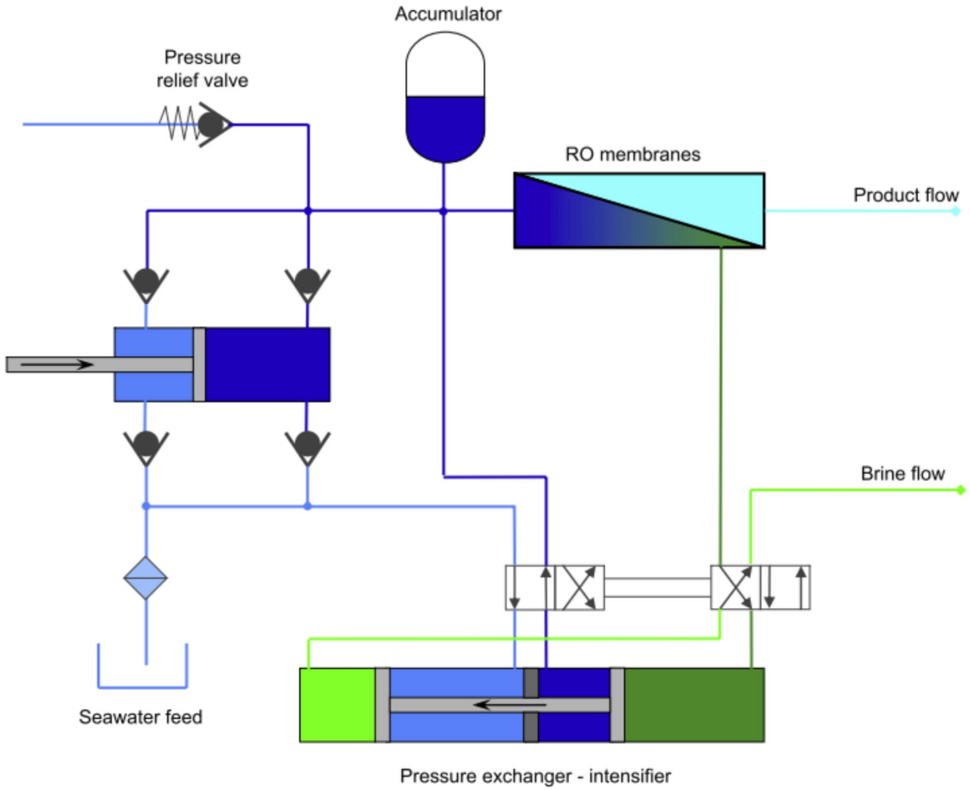


Hydraulic PTOs for RO: Folley et al.

- **Folley et al., 2008**
  - production rate as function of:
    - Membrane area
    - Accumulator volume

- **Folley and Whitaker, 2009**
  - cost of water as function of plant capacity





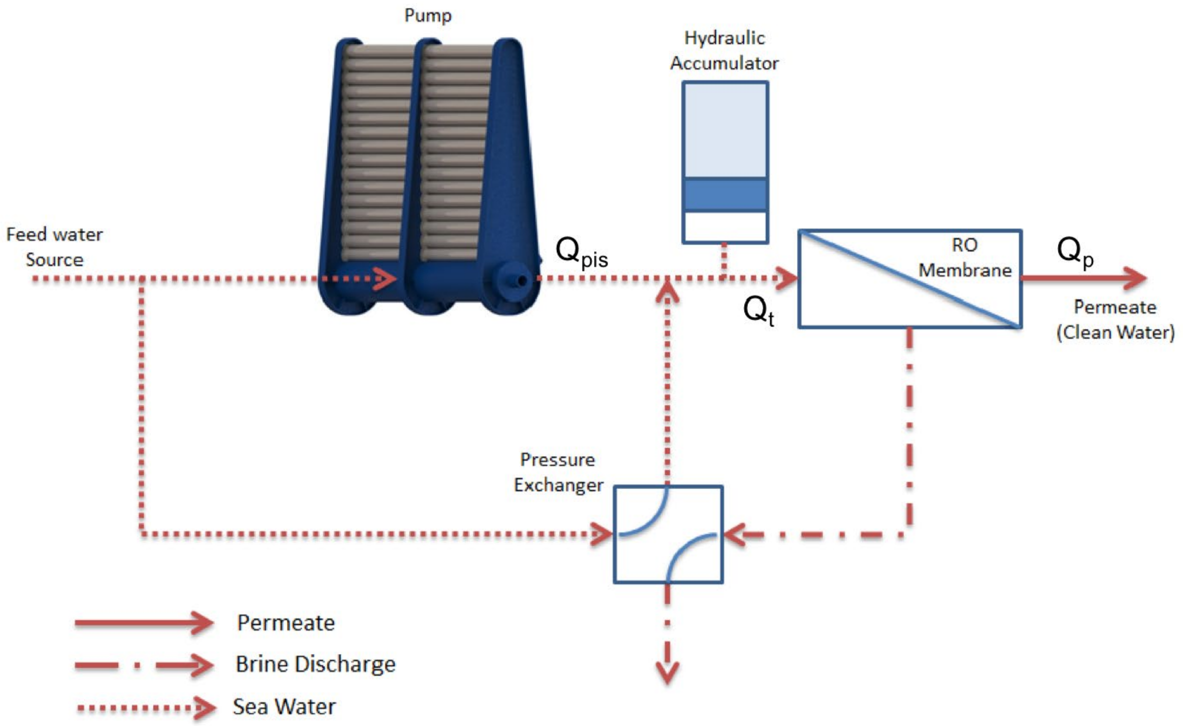
Folley et al., 2008, "An autonomous wave-powered desalination system," Desalination

(Left and Right) Folley and Whittaker, 2009, "The cost of water from an autonomous wave-powered desalination plant," Renewable Energy

Hydraulic PTOs for RO: Yu et al.

- **Yu and Jenne, 2017**
  - cost of water as function of plant capacity

- **Yu and Jenne, 2018**
  - effect of accumulator volume on
    - Production rate
    - Pressure variation
    - Product salinity

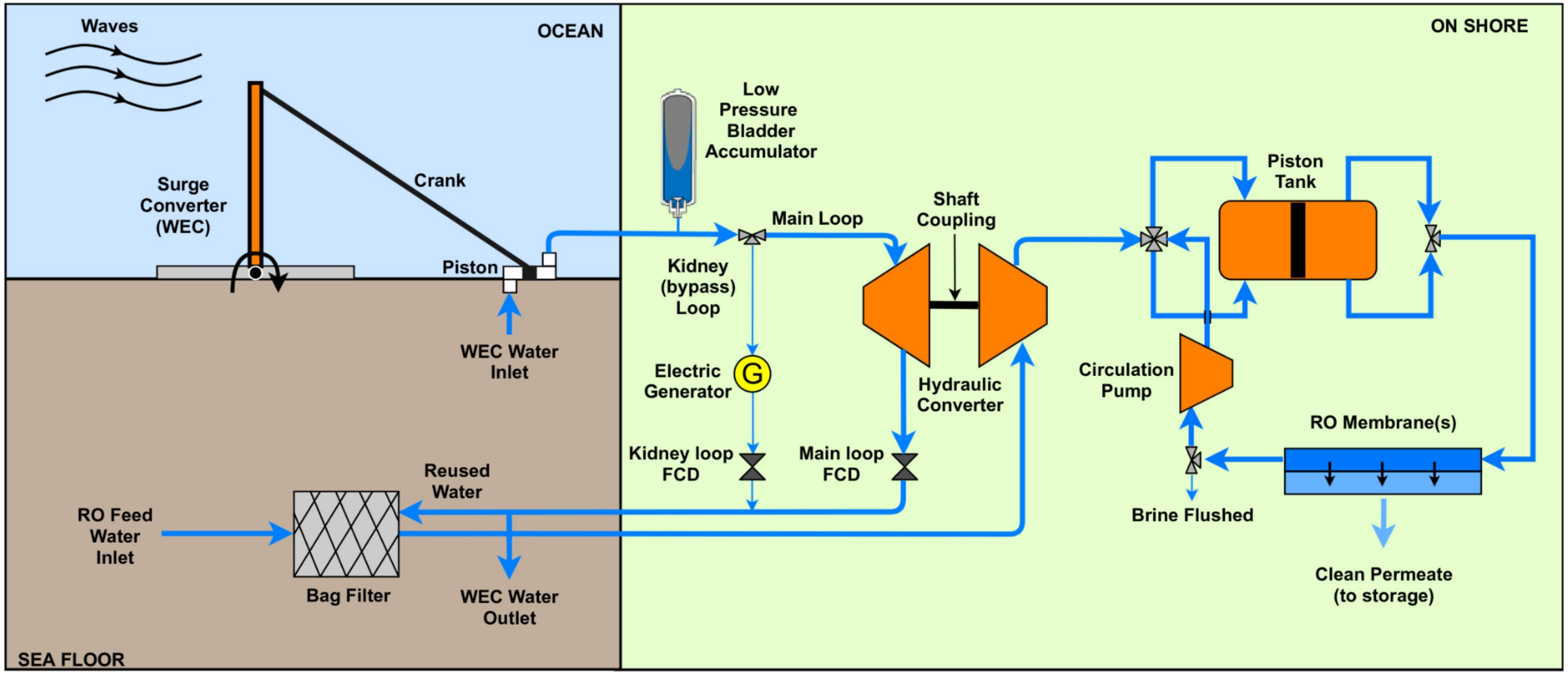


Yu and Jenne, 2017, "Analysis of a wave-powered, reverse-osmosis system and its economic availability in the United States," International Conference on Offshore Mechanics and Arctic Engineering

Yu et al., 2018, "Numerical analysis on hydraulic power take-off for wave energy converter and power smoothing methods," International Conference on Offshore Mechanics and Arctic Engineering

Hydraulic PTOs for RO: Brodersen et al., 2022

- **Brodersen et al., 2022**
  - Efficiency vs. recovery ratio of batch RO process
  - Estimate for cost of water



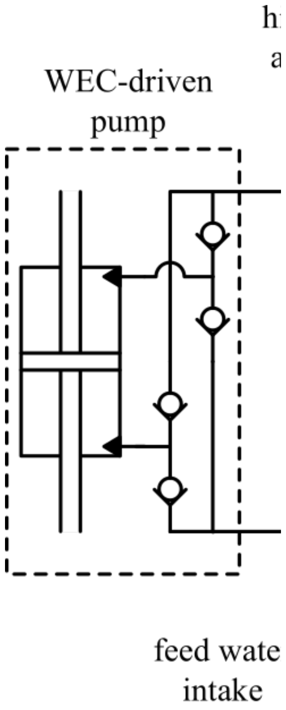
(Above) Brodersen, et al., 2022,"Direct-drive ocean wave-powered batch reverse osmosis," Desalination, 523, p. 115393.

Overview

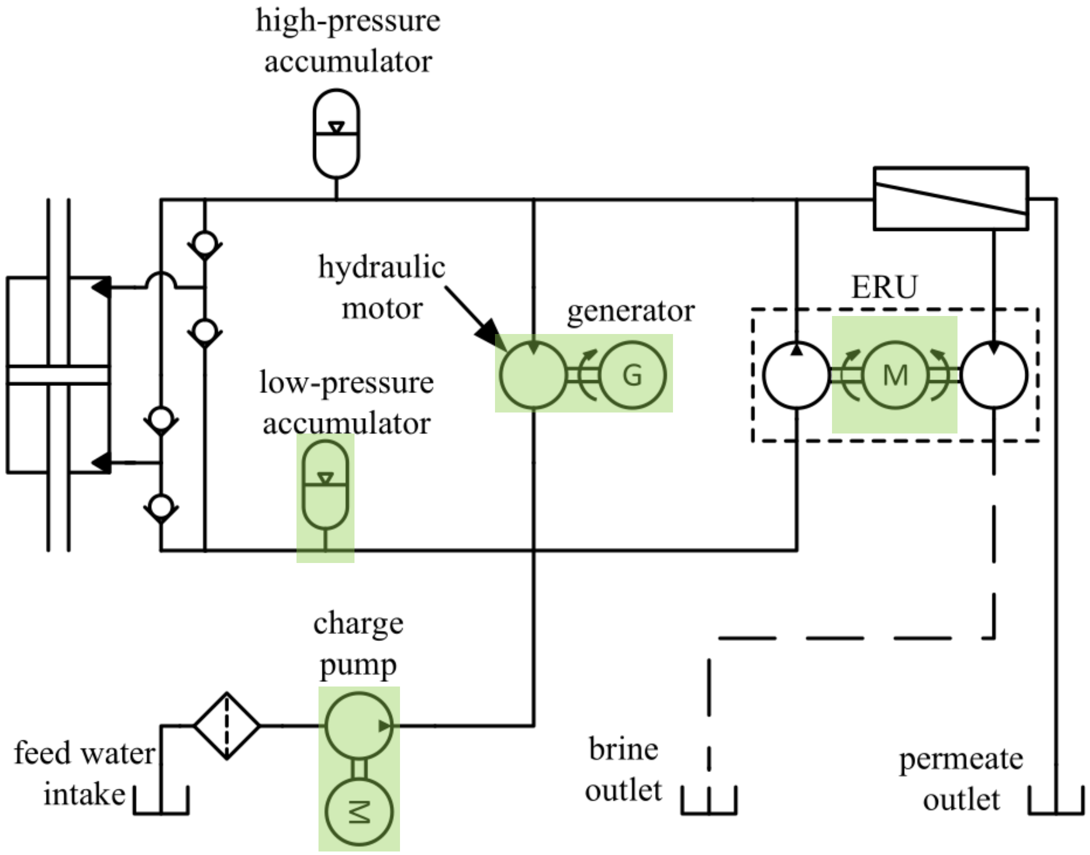
- Challenge of a direct seawater intake without a charge pump
- Analysis of pressure losses and risk of cavitation
- How component sizes (needed to avoid cavitation) compare to the overall system scale
- Design analysis with charge pump included
- Take-aways

Baseline PTO Architecture

Prior works



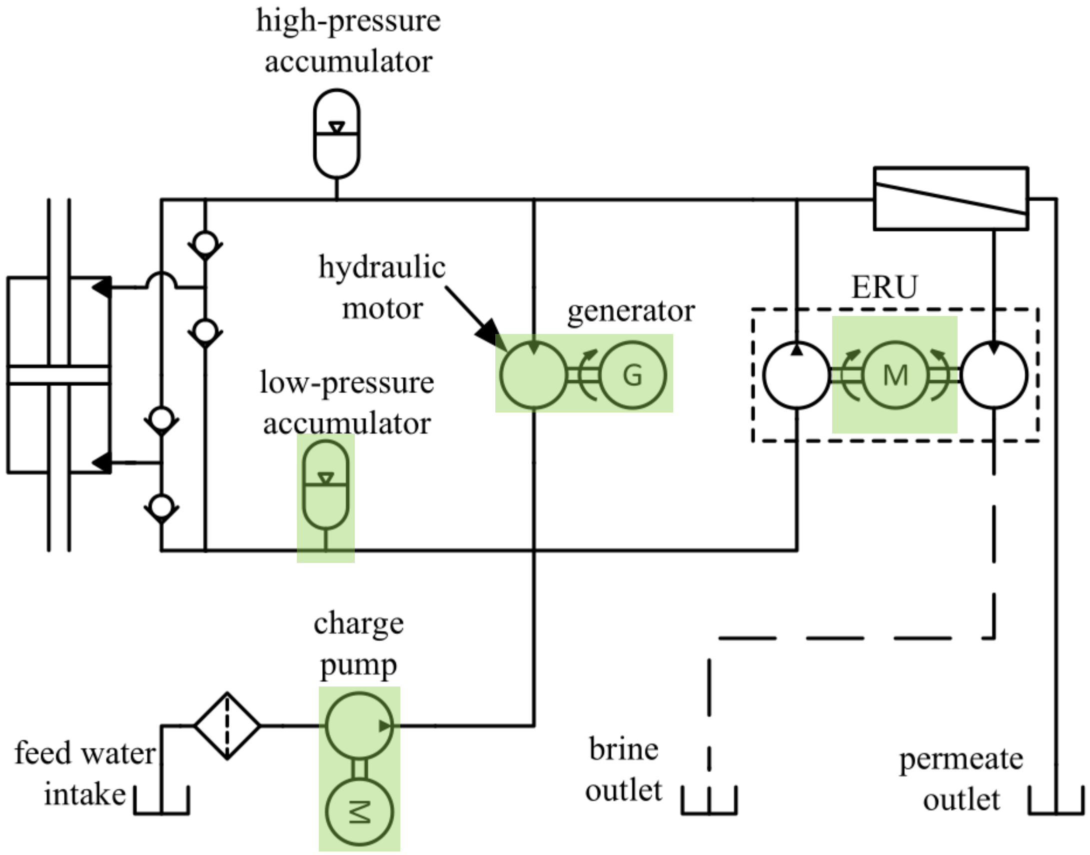
With Elec. Power production



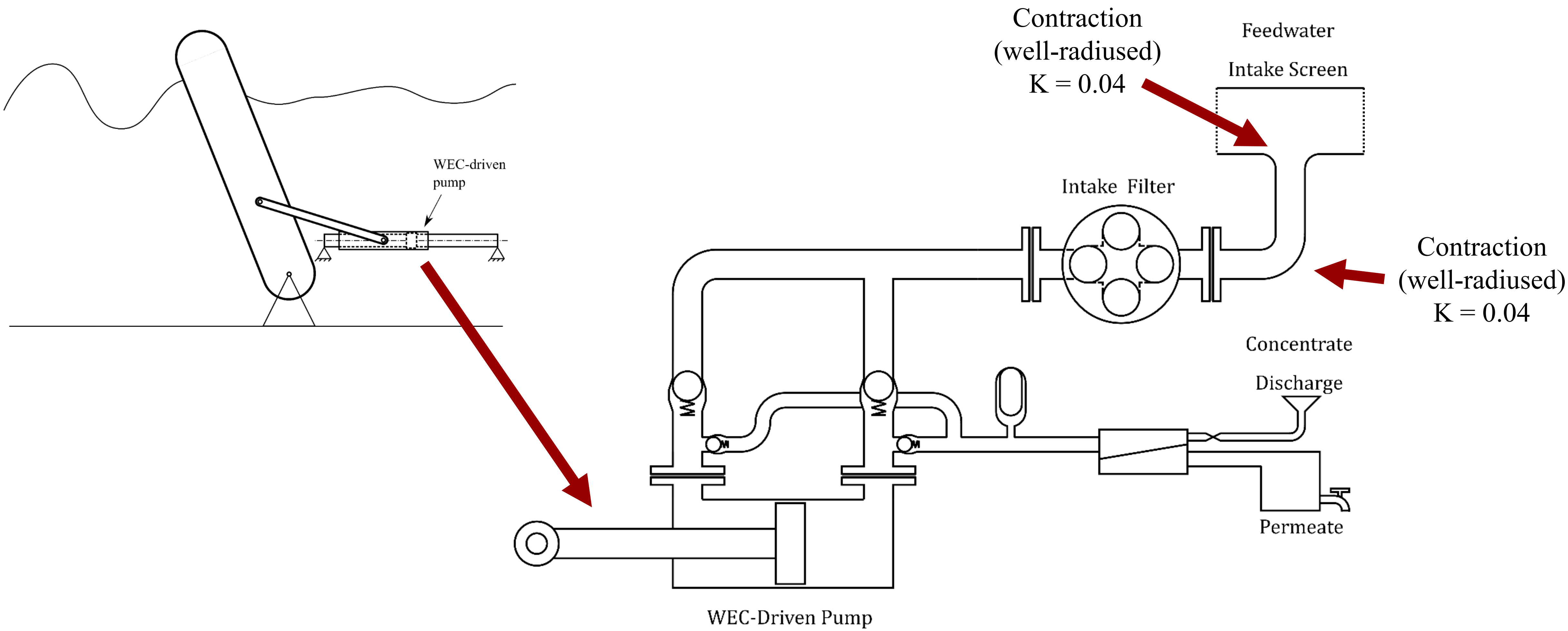
Need for a Charge Pump

- Pressure losses present a risk of cavitation
- Loss sources:
  - Intake filter (5μm filter)
  - Check valves
  - Major and minor piping losses
- High peak-to-mean ratio in WEC velocity (e.g., 4:1 - 10:1)

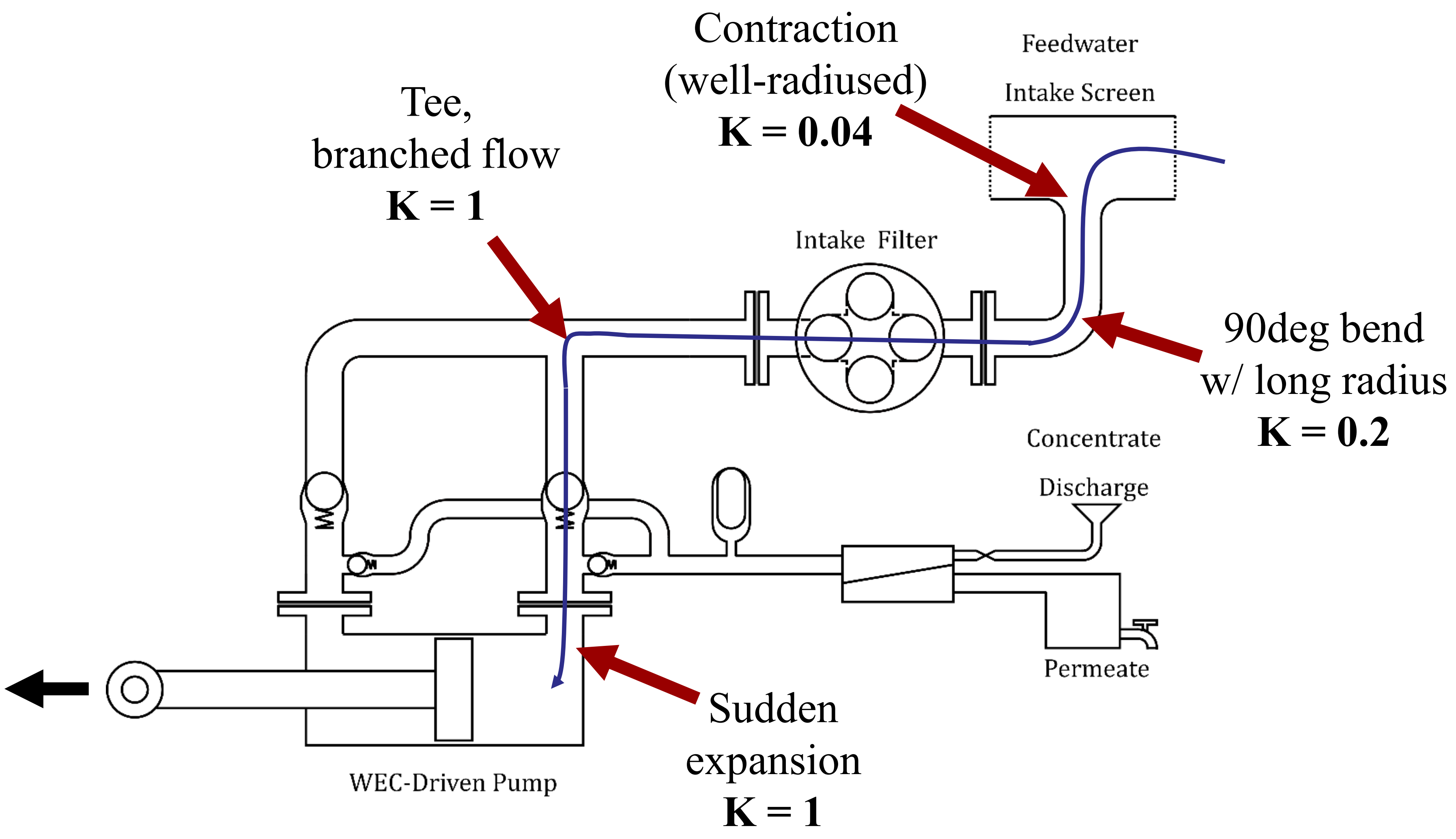
With Elec. Power production



A Barebones Circuit

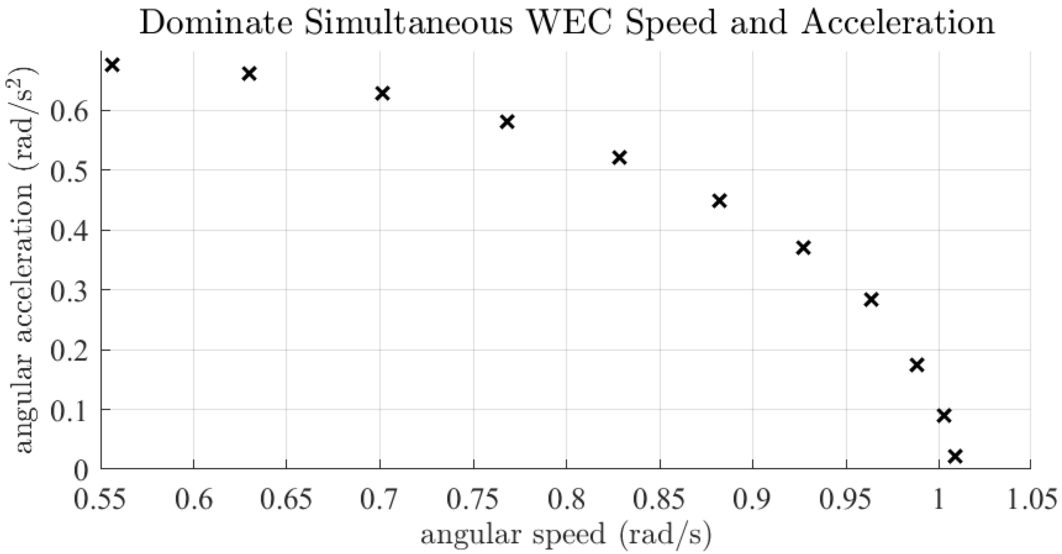


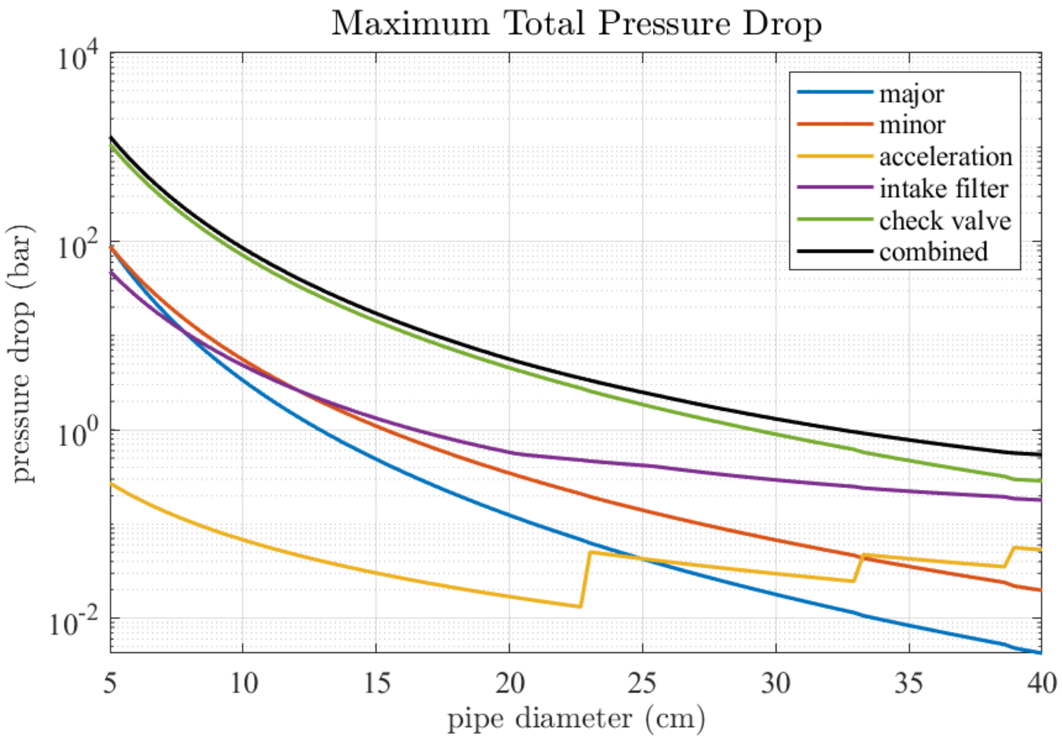
Minor Losses



Pressure Loss Sources Compared

- Peak velocity and acceleration conditions from dynamic simulations
- Check valve losses are dominant
- Filter resistance is significant
- Minor losses are greater than major losses
- Total losses on the order of 1-10 bar





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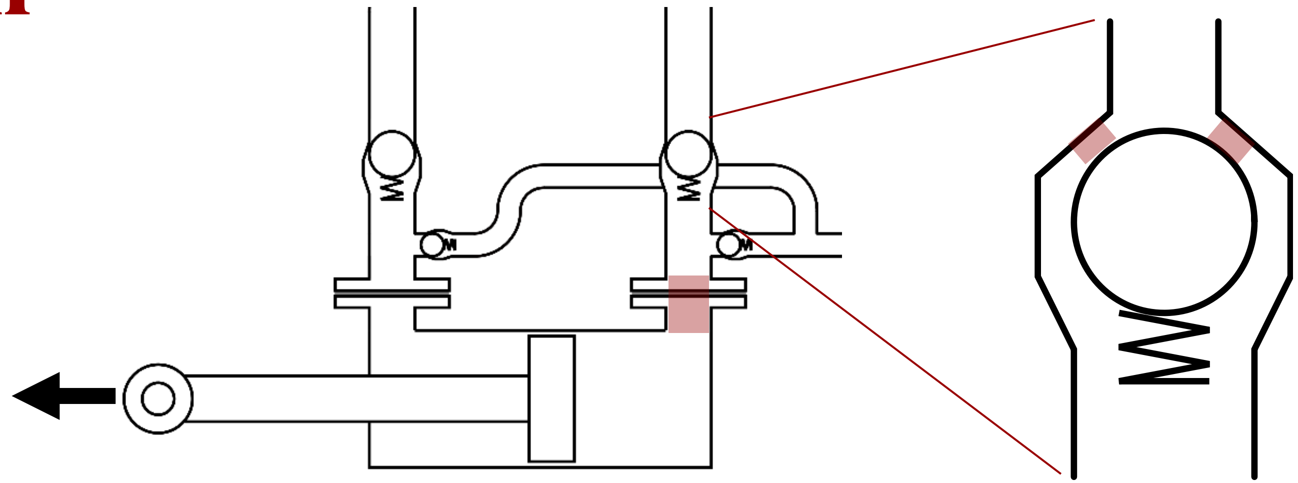
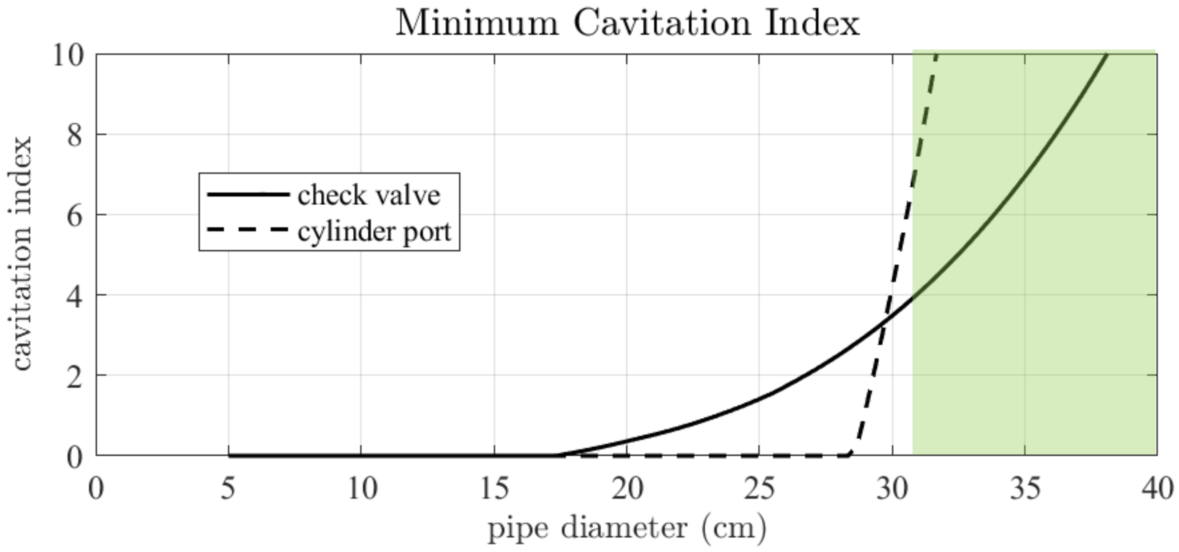
Analysis of Cavitation

- Cavitation index, a measure of cavitation potential
  - Possible: 2 – 4
  - Likely: 2.5
- Cavitation most likely at
  - **Check valve restriction** or
  - **Porting within the WEC-driven pump**

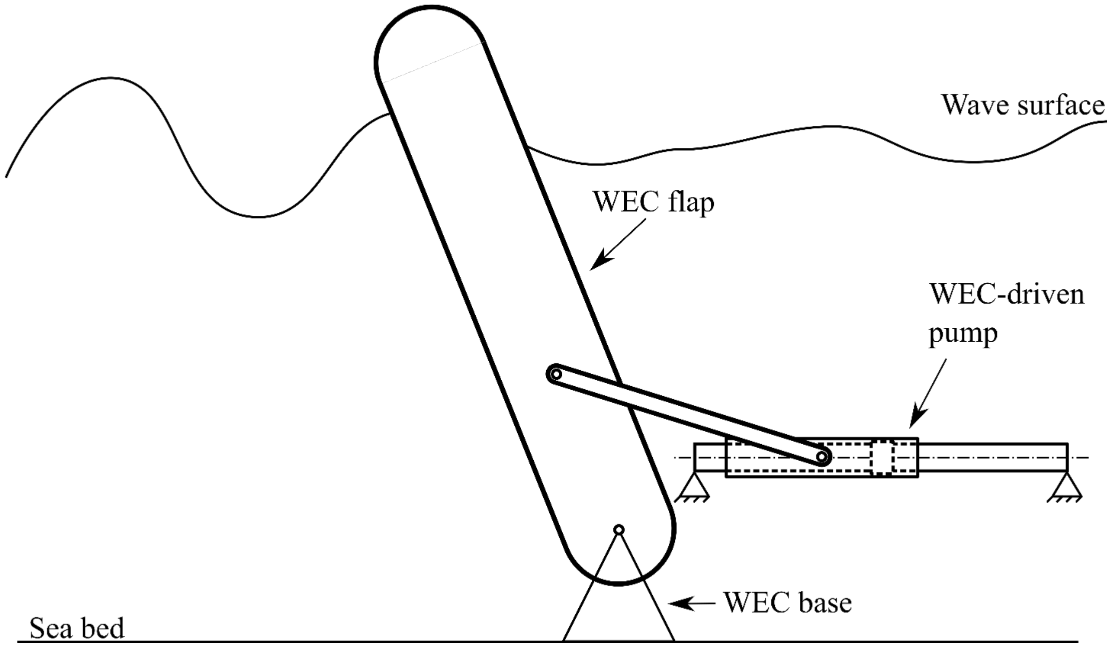
$$Caviation\ Index = \frac{static\ pressure\ - vapor\ pressure}{dynamic\ pressure}$$





System Scale

- **Drawing is to scale** for Yu and Jenne 2017 and Brodersen et al. 2022
- Pump displacement from Simmons and Van de Ven 2023
- 150–200 kW average power capture
- 18m wide, 13m tall
- 11m water depth
- Internal diameter of cylinder pump is 0.6m
- **Required pipe and check valve diameter (>30 cm) are more than half the diameter of the pump**



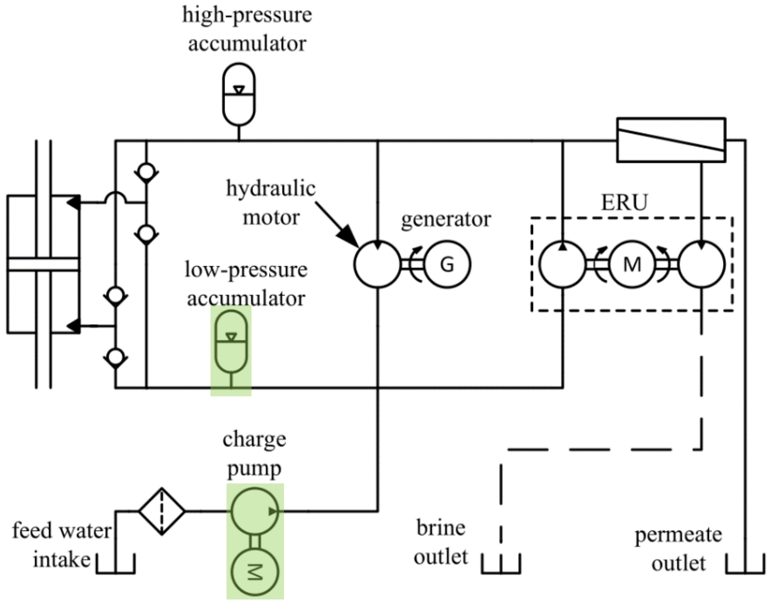
Yu and Jenne, 2017, “Analysis of a wave-powered, reverse-osmosis system and its economic availability in the United States,” International Conference on Offshore Mechanics and Arctic Engineering

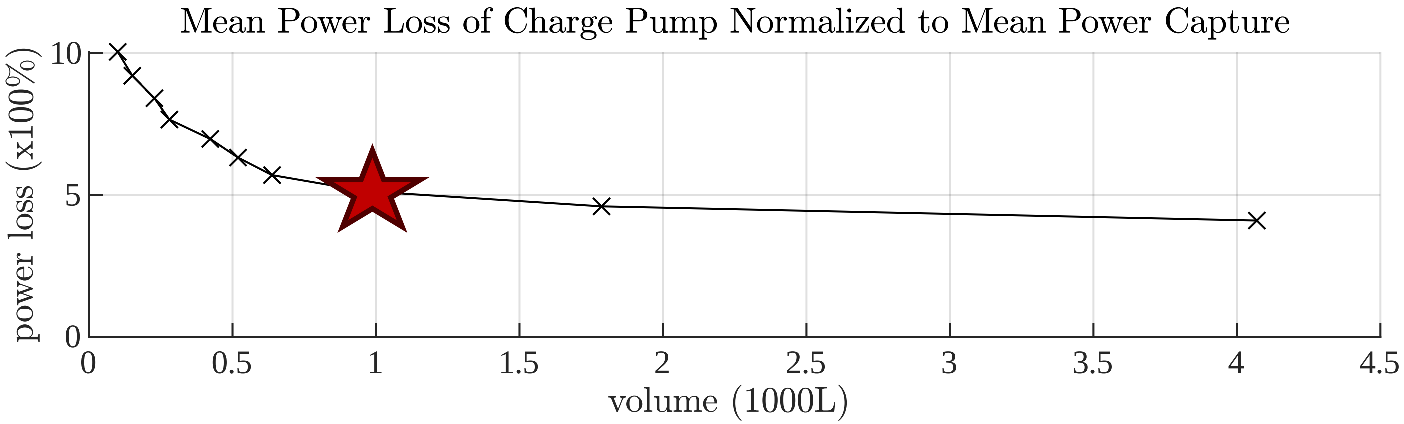
Brodersen, et al., 2022,“Direct-drive ocean wave-powered batch reverse osmosis,” Desalination, 523, p. 115393.

Simmons and Van de Ven, 2023, “A Comparison of Power Take-Off Architectures for Wave-Powered Reverse Osmosis Desalination of Seawater with Co-Production of Electricity,” Energies

Design Including Charge Pump

- Design by grid search
- Objectives:
  - Minimize power loss
  - Minimize accumulator volume
- Constraints
  - Minimum pressure in WEC-driven pump
- Variables
  - Charge pump speed
  - Accumulator volume





Simmons, Jeremy W., 2024, "Modeling and Design of Power Take-Offs for Ocean Wave-Powered Reverse Osmosis Desalination," PhD Thesis, University of Minnesota

Take-Aways

- Attempts to implement a direct seawater intake maybe costly
  - Large piping and check valves that address extreme corner conditions

- Adding a charge pump (and accumulator) allows for elevated pump intake pressure
  - This is a practice typical of conventional hydraulic systems

- A charge pump will account for approximately 5% of total system losses
  - It does work that needs to be done anyway. It is just slightly less efficient (e.g., 70% vs 85%).

- 1000 liters of accumulator volume is used.
  - This is significantly less than is needed in the high-pressure branch (4,000-18,000 liters*)

* Simmons, Jeremy W., and James D. Van de Ven. 2024 ”Design of Hydraulic Power Take-Offs for Wave-Powered Reverse Osmosis Desalination: Meeting Constraints on Pressure Variation”, In 2024 Global Fluid Power Society PhD Symposium. (In print)

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