NAWI National Alliance for Water Innovation

Investigating High Pressure Reverse Osmosis

Task 3.7 Analysis

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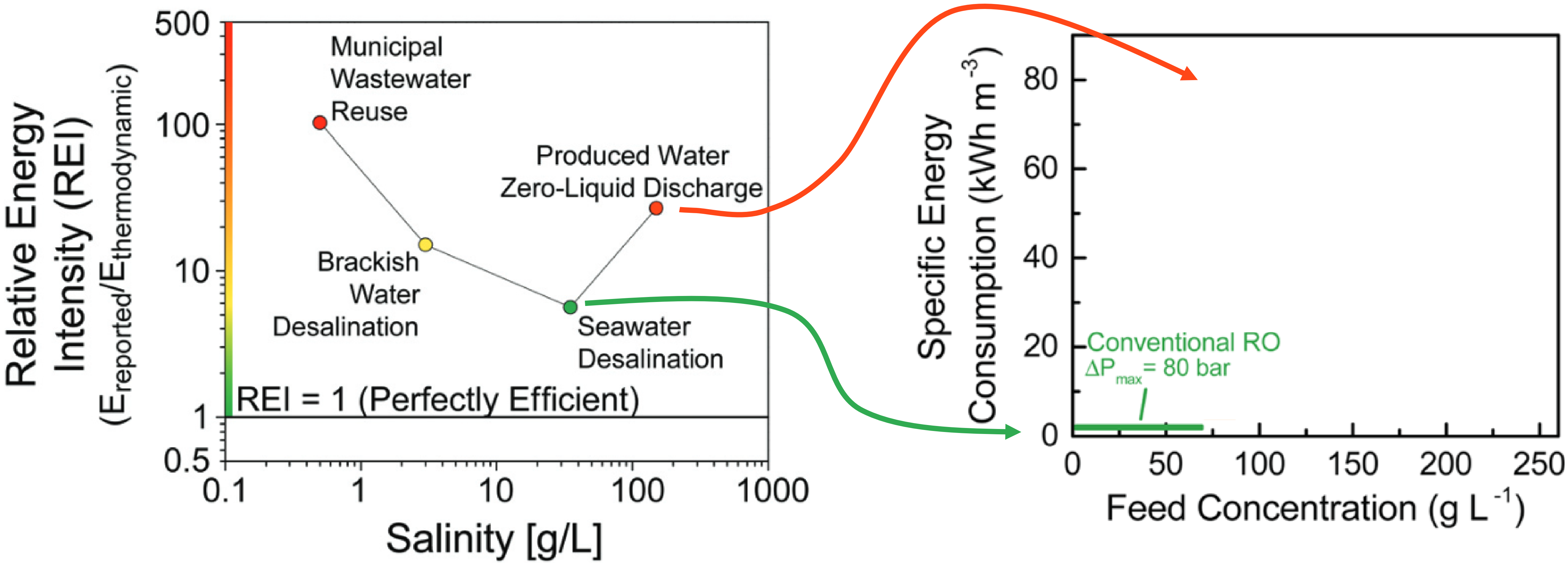
May 3, 2022

Low salinity and high salinity waters require innovations to reduce energy use and cost

What would the *cost* of HPRO be with *current state of the art* and *future* components?



Mauter, M. S. & Fiske, P. S. Desalination for a circular water economy. *Energy & Environmental Science* **13**, 3180–3184 (2020).

Davenport, D. M., Deshmukh, A., Werber, J. R. & Elimelech, M. High-Pressure Reverse Osmosis for Energy-Efficient Hypersaline Brine Desalination: Current Status, Design Considerations, and Research Needs. *Environ. Sci. Technol. Lett.* **5**, 467–475 (2018).

WaterTAP enables simulation of full HPRO system

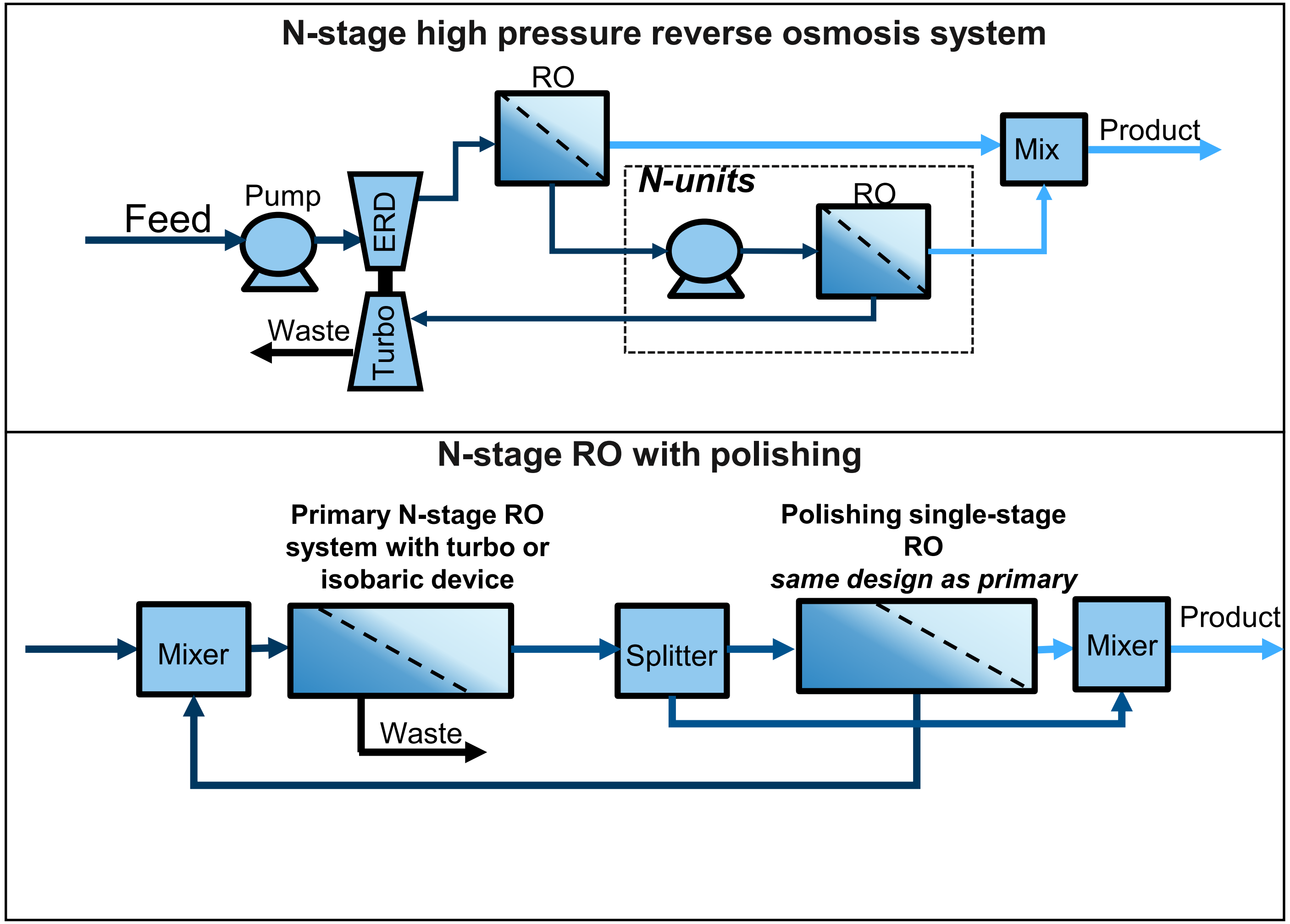
WaterTAP provides standard unit models:

- Standard 1D reverse osmosis model
- Standard pump model (from IDAES)
- Turbo energy recovery device (ERD) –made by coupling mechanical energy transfer between two standard ERD pump devices (from IDAES)

Multi-stage build is enabled by IDAES

Model only needs to be modified to account for:

1. *Pressure effect on* ***component cost***
2. *Pressure effect on* ***membrane performance***



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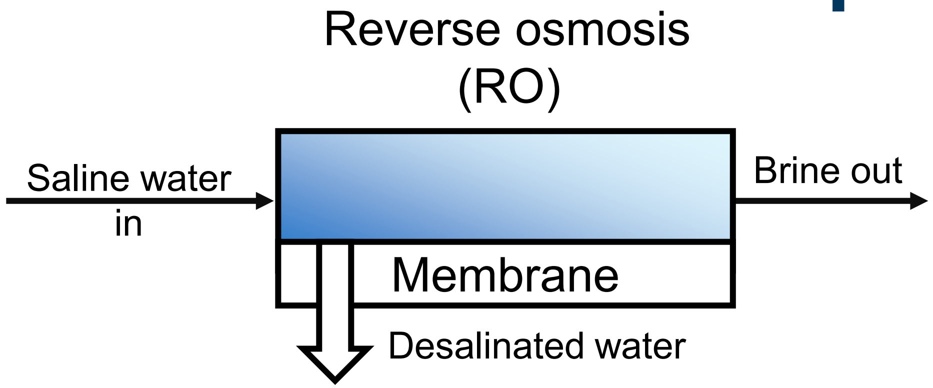
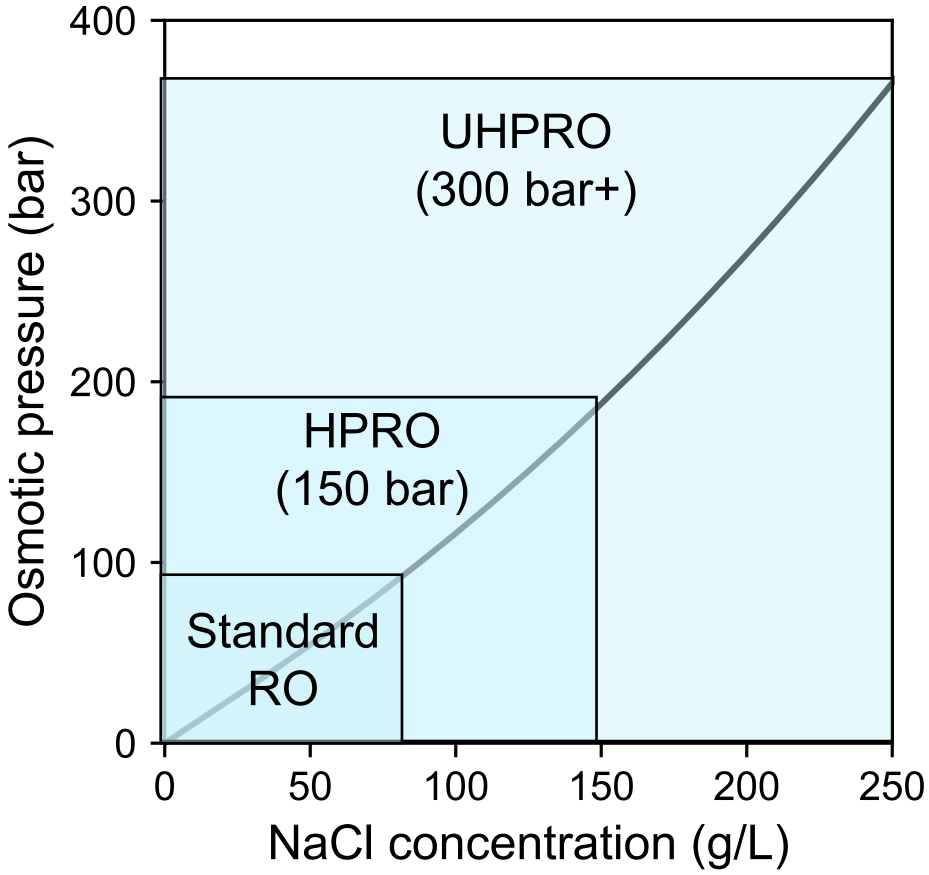
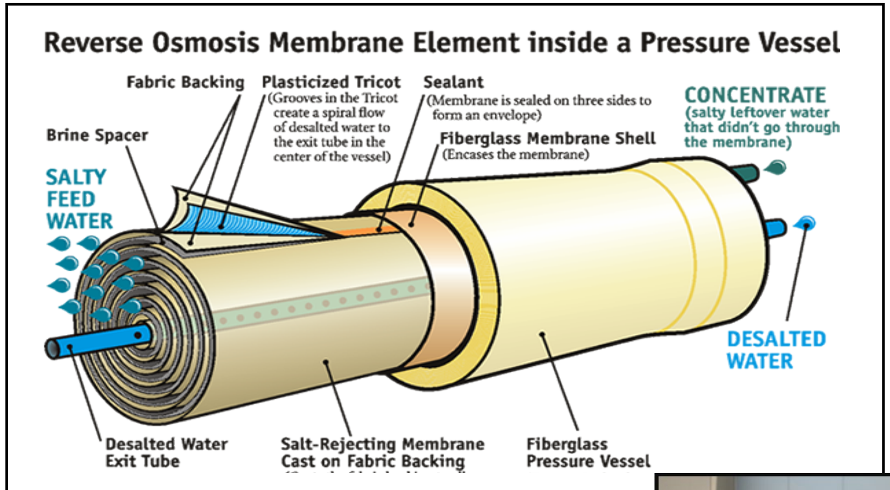
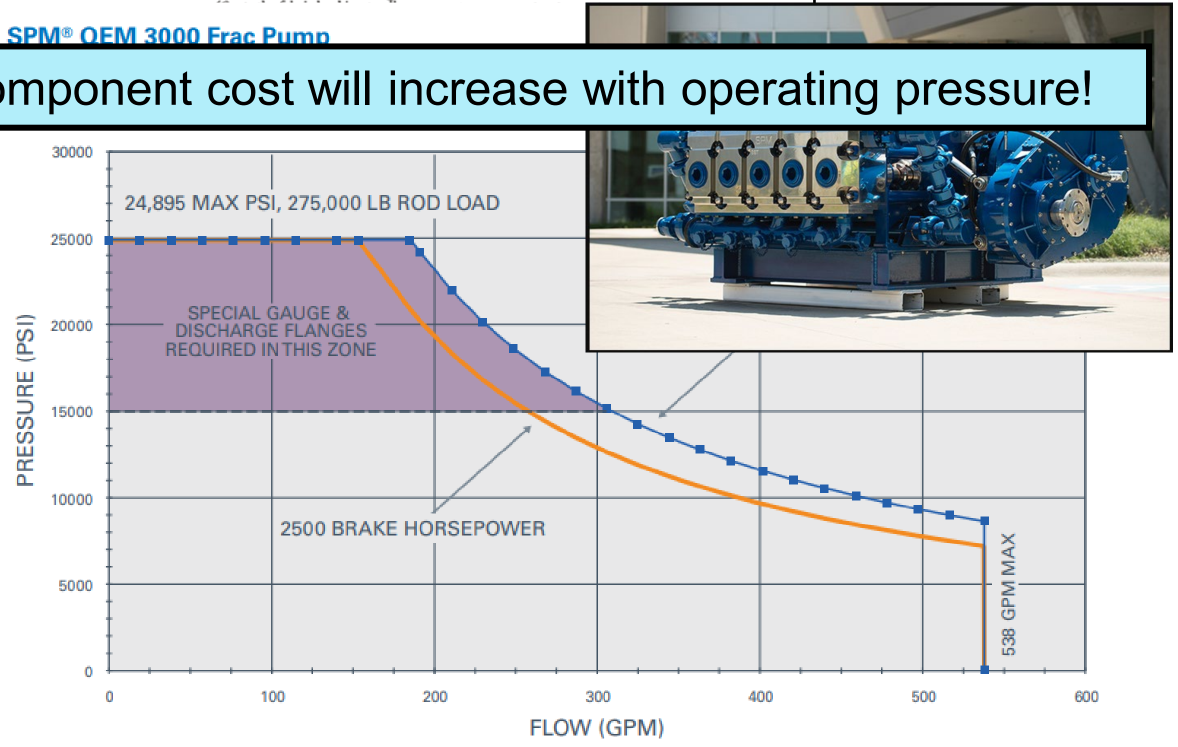
HPRO will have to operate at pressures above 200 bar







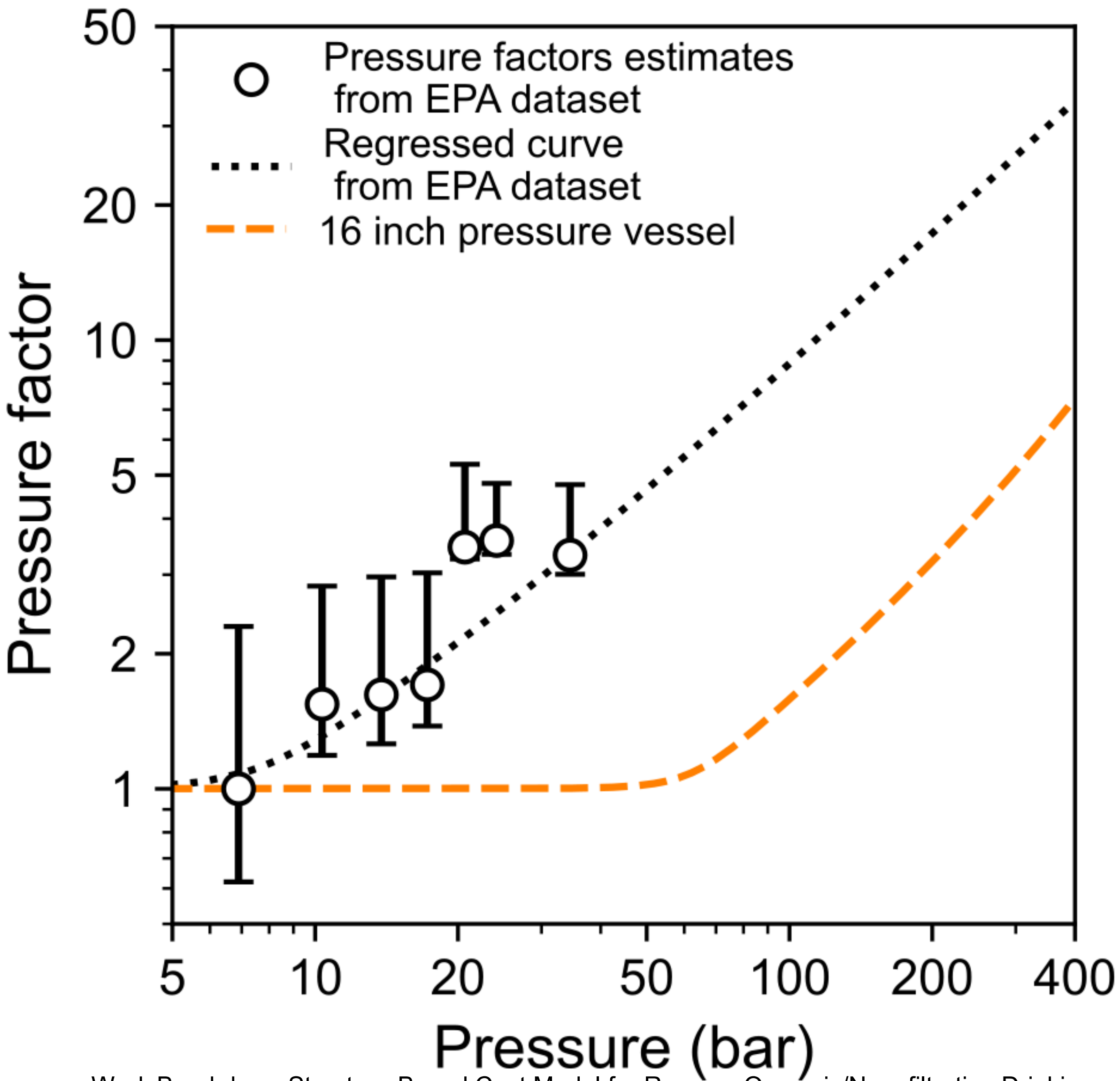
Component cost will increase with operating pressure!



Pressure factors can be used to project cost increase with pressure ($CC_{hp}=f_p*CC_{lp}$)

Considered scenarios:

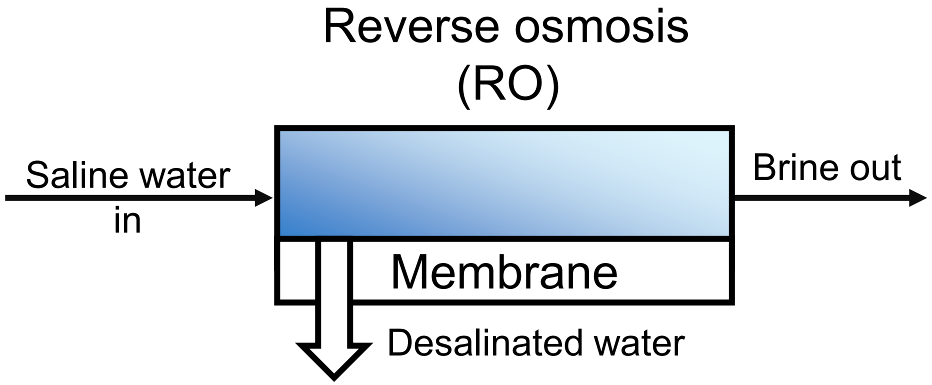
1. **Ideal scenario**
   - Membrane performance does not decrease with pressure
   - Component costs do not increase with pressure
2. **HP cost scenario**
   - Membrane performance does not decrease with pressure
   - Component costs increase with pressure

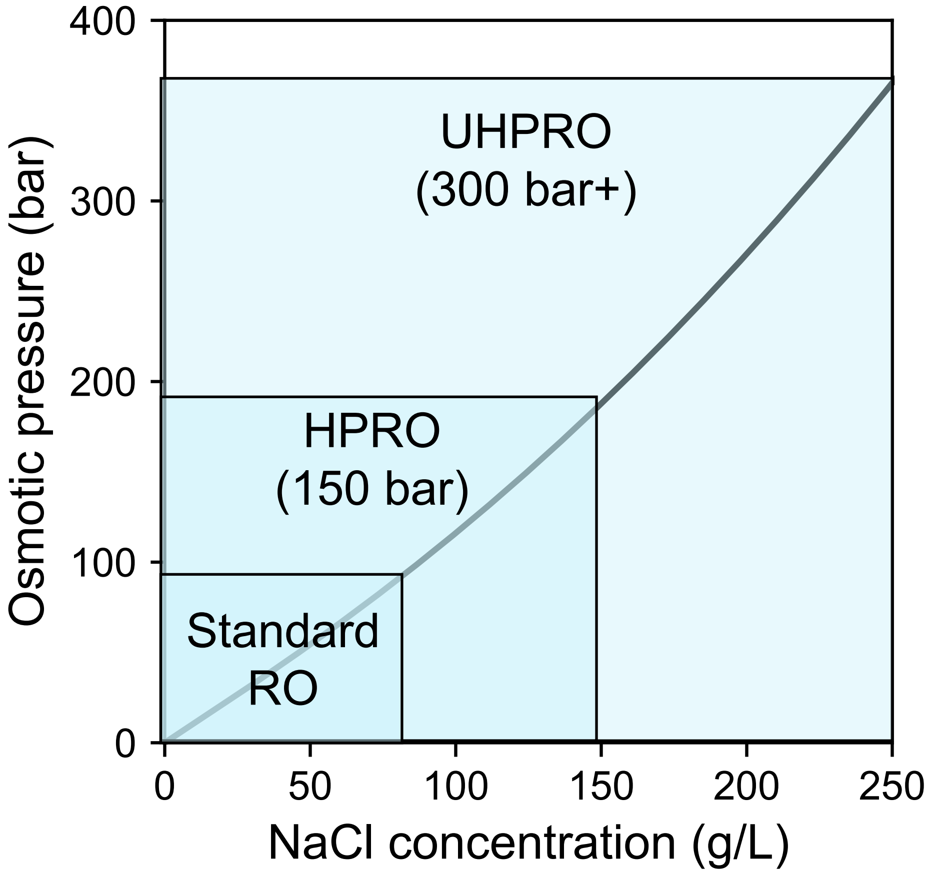


Work Breakdown Structure-Based Cost Model for Reverse Osmosis/Nanofiltration Drinking Water Treatment. 130.

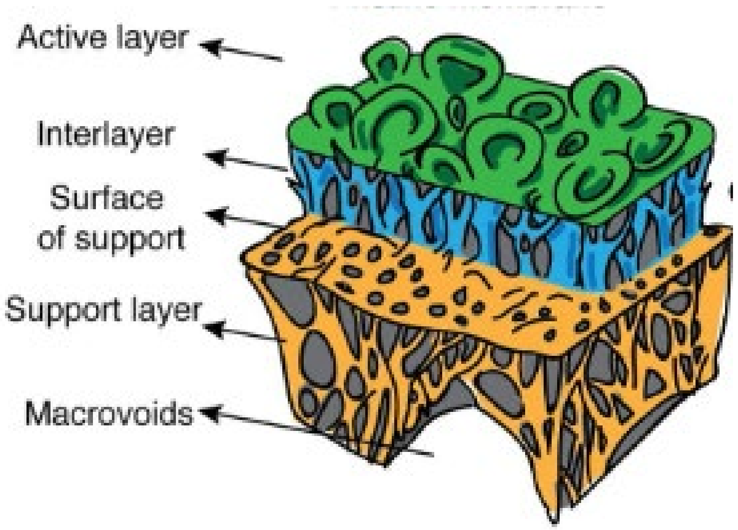
Turton, R. *Analysis, synthesis, and design of chemical processes*. (Prentice Hall, 2012).

Membrane performance in high pressure RO

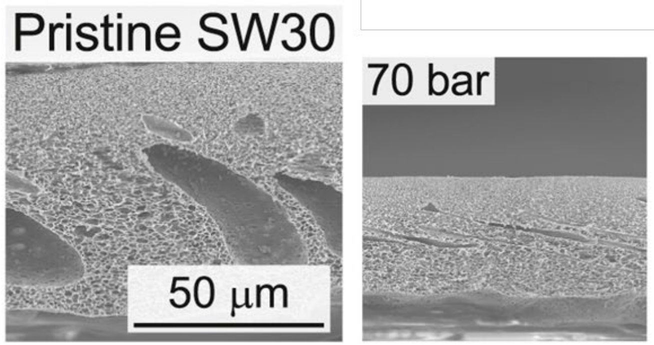




Membrane performance degrades with increasing pressure!



Chen, X., Boo, C. & Yip, N. Y. Transport and structural properties of osmotic membranes in high-salinity desalination using cascading osmotically mediated reverse osmosis. *Desalination* **479**, 114335 (2020).

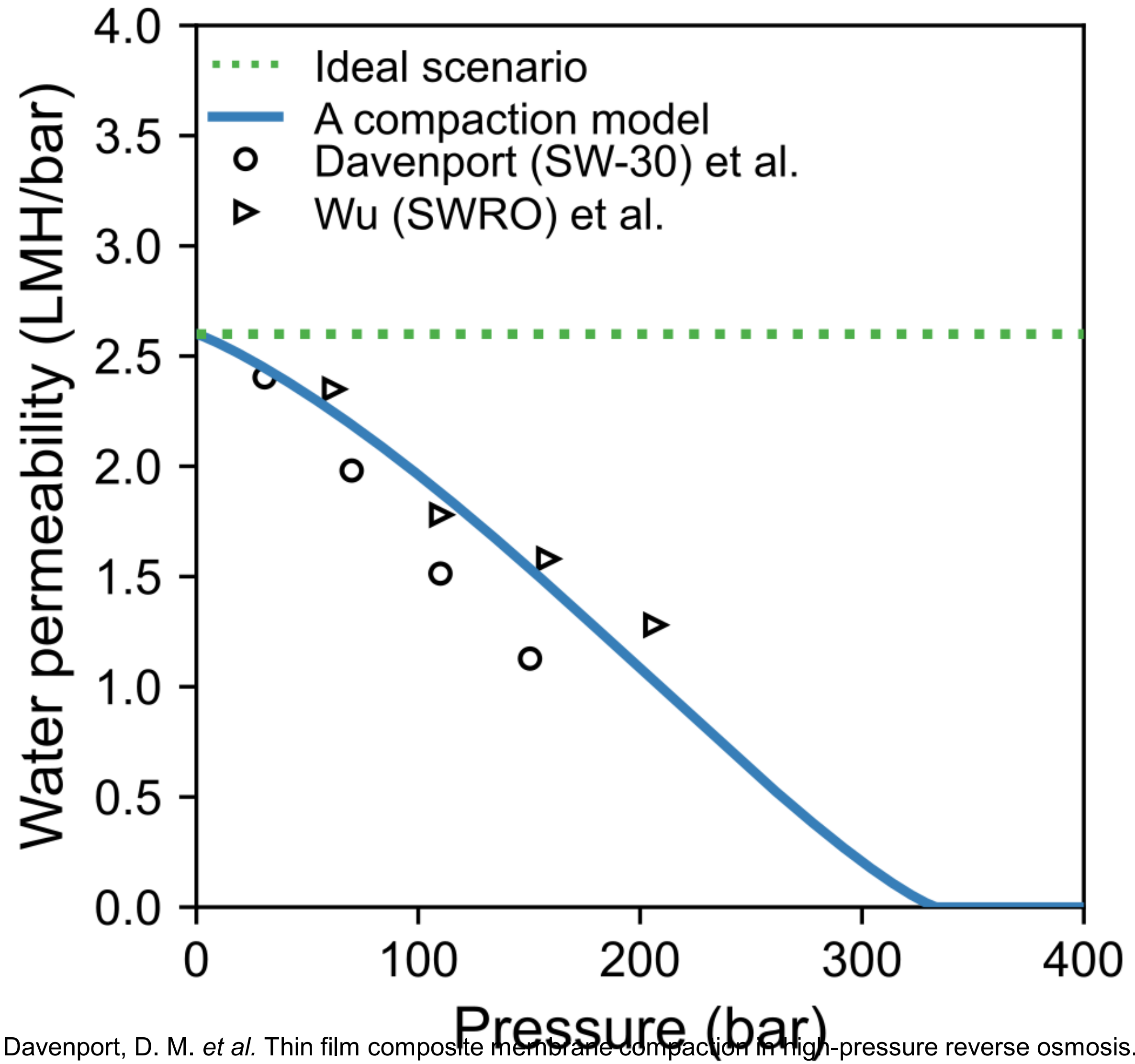


Davenport, D. M. *et al.* Thin film composite membrane compaction in high-pressure reverse osmosis. *Journal of Membrane Science* 118268 (2020) doi:10.1016/j.memsci.2020.118268.

Performance scenarios help understand process performance potential

Considered scenarios:

1. **Ideal scenario**
   - Membrane performance does not decrease with pressure
   - Component costs do not increase with pressure
2. **HP cost scenario**
   - Membrane performance does not decrease with pressure
   - Component costs increase with pressure
3. **A compaction scenario**
   - Membrane water permeability degrade
   - Component costs increase with pressure



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Wu, J. *et al.* Reverse osmosis membrane compaction and embossing at ultra-high pressure operation. *Desalination* **537**, 115875 (2022).

Performance scenarios help understand process performance potential

Considered scenarios:

1. **Ideal scenario**
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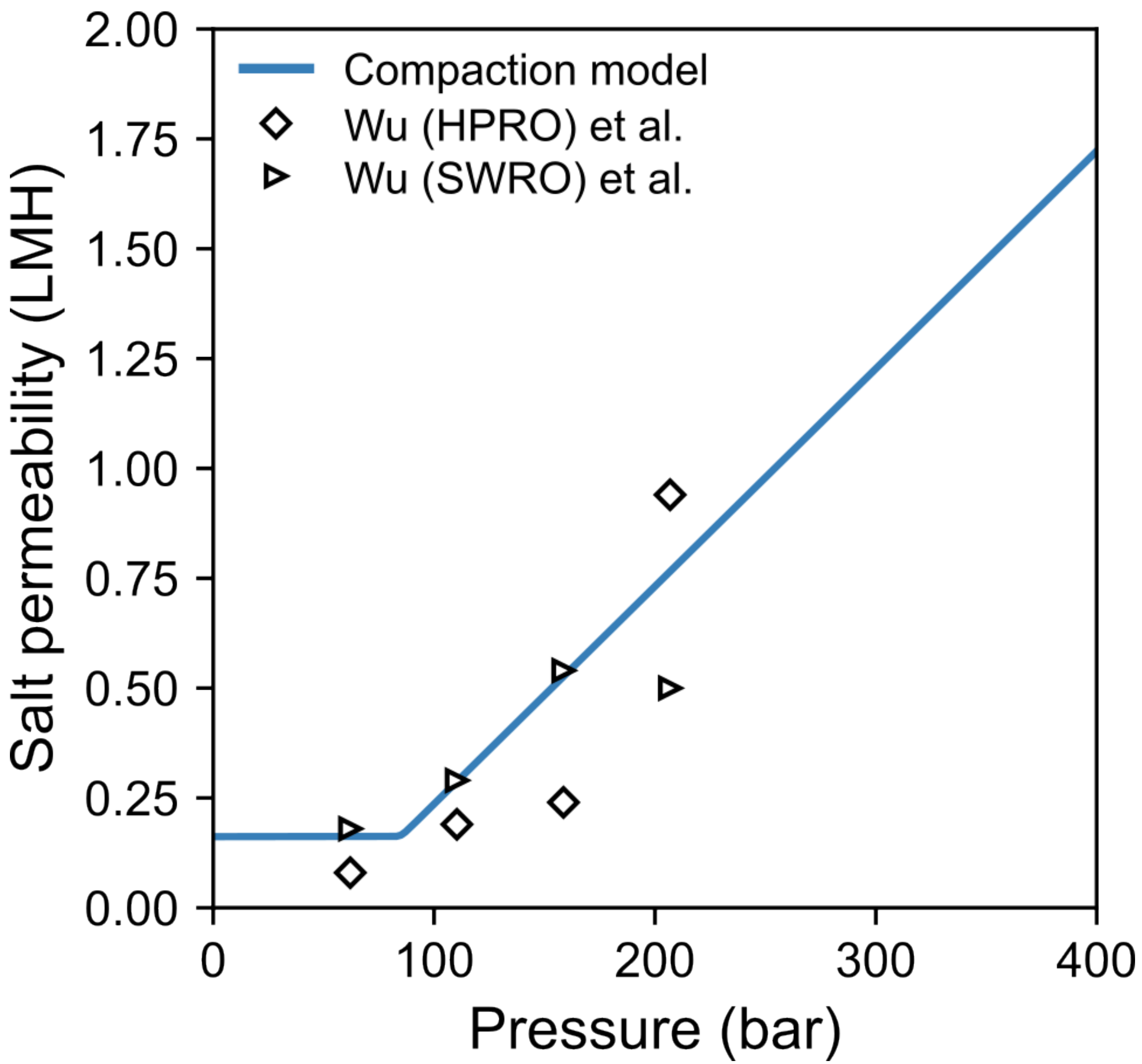
2. **HP cost scenario**
   - Membrane performance does not decrease with pressure
   - Component costs increase with pressure
3. **A compaction scenario**
   - Membrane water permeability degrade
   - Component costs increase with pressure
4. **A & B compaction scenario**
   - Membrane water and salt permeability degrade
   - Component costs increase with pressure



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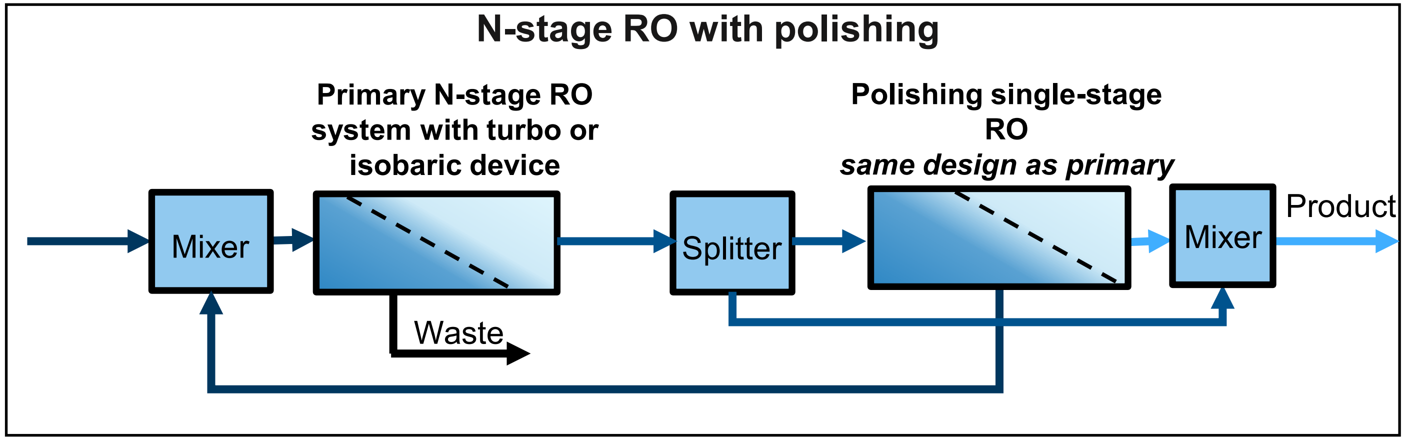
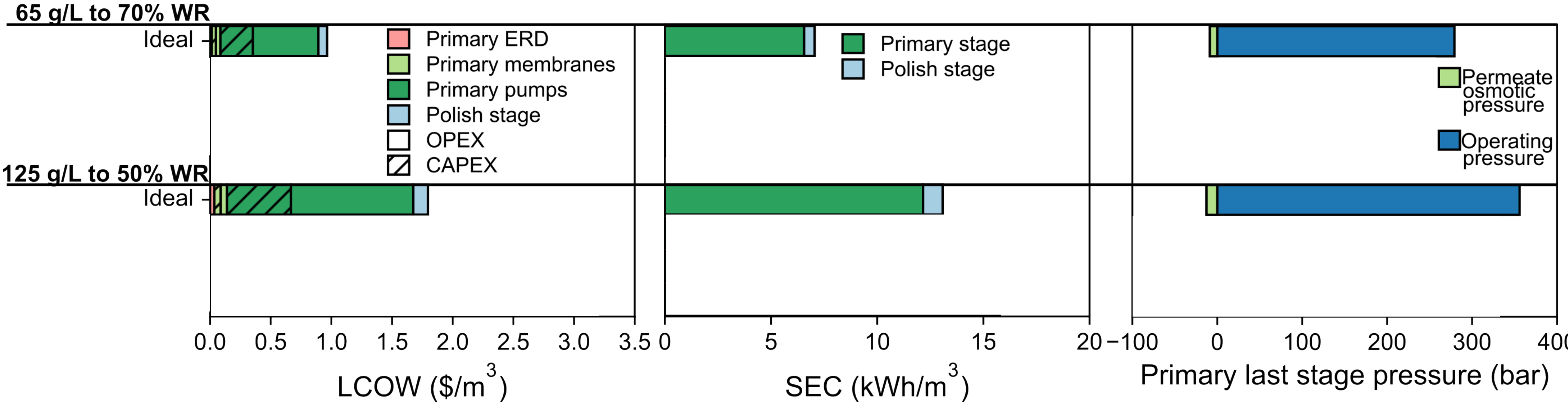
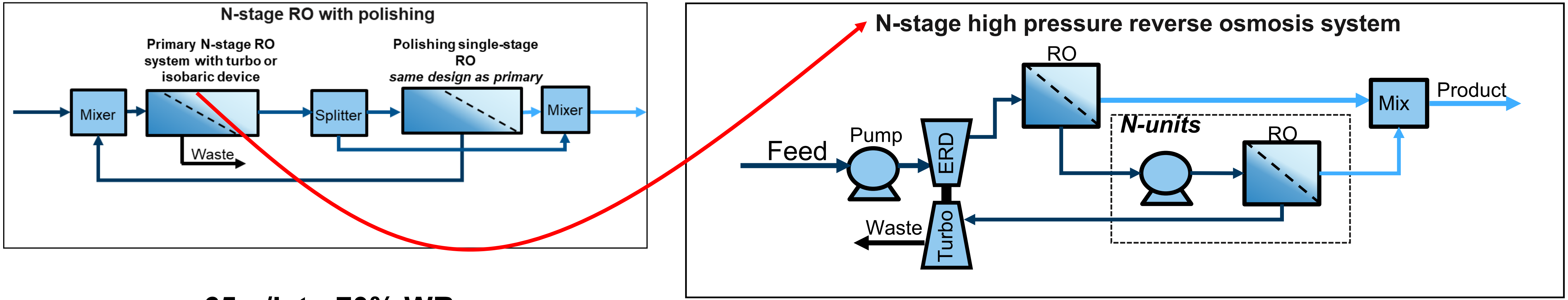
Pump costs govern HPRO LCOW and design

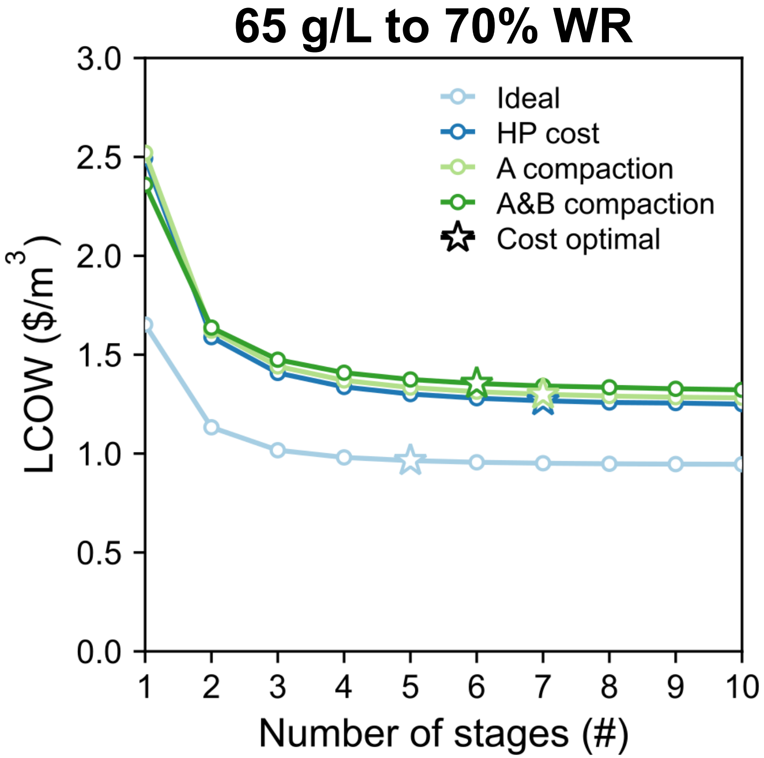


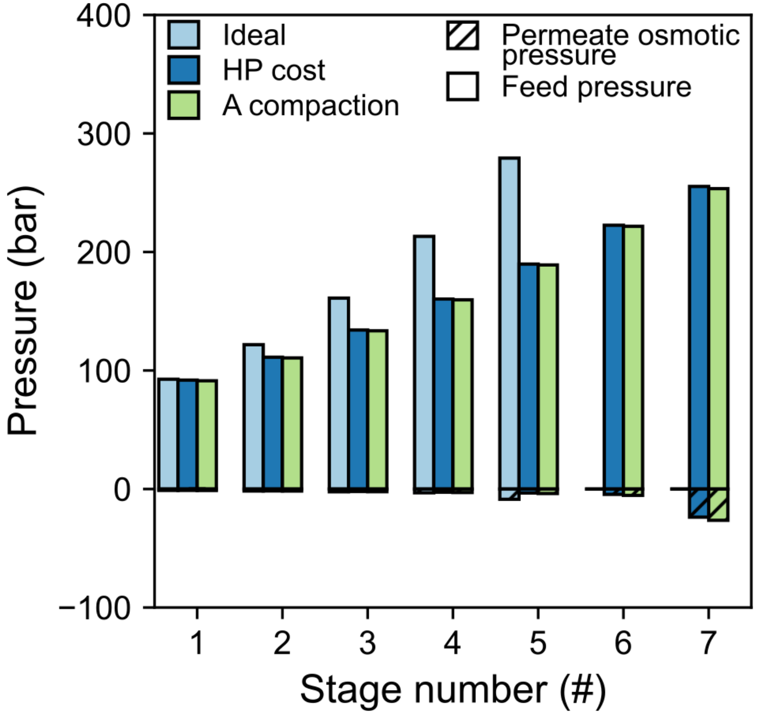
1. Under ideal scenario – pumps dominate costs
2. Inclusion of pressure effect on component costs increases LCOW by 25 – 40%
3. Membrane compaction effect can be mitigated by changing operational mode of HPRO process

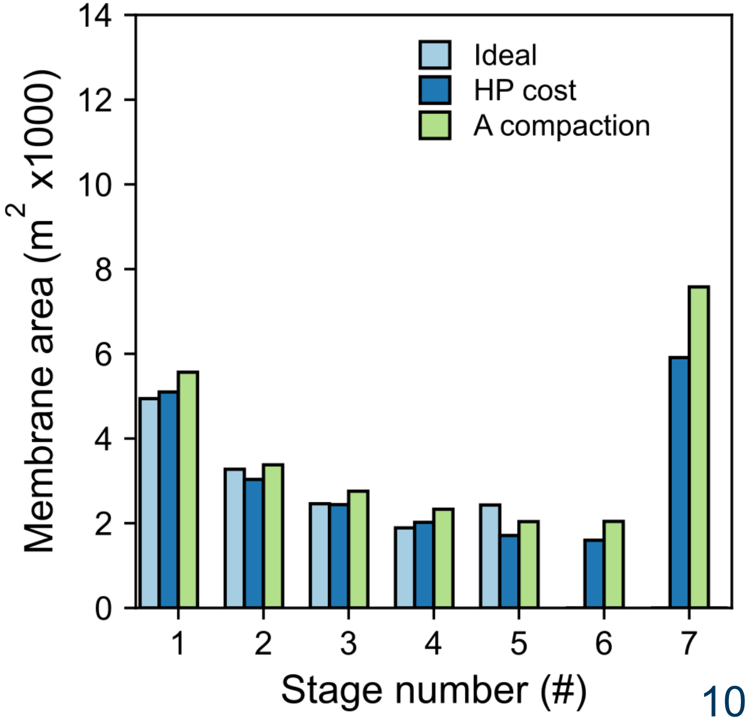


Multi-staging reduces impact of high pressures and cost









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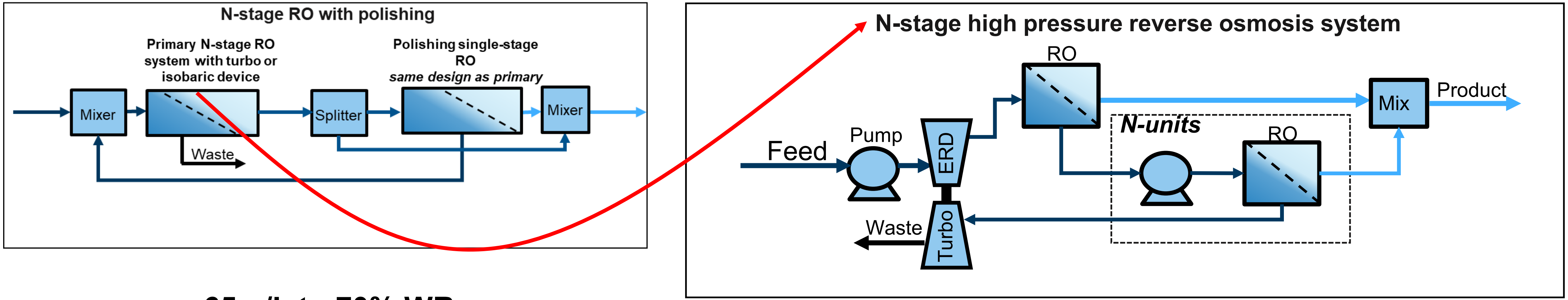
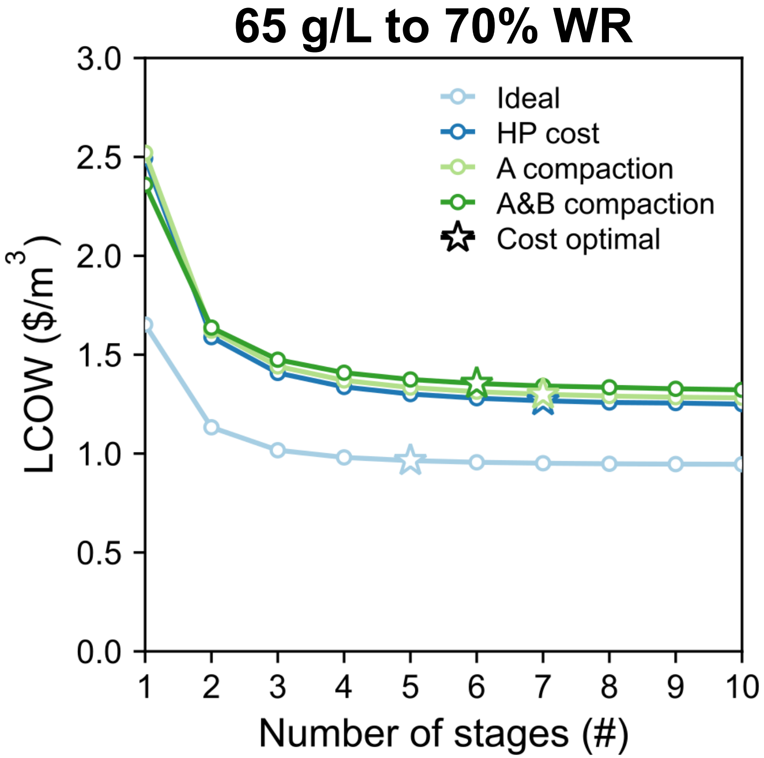
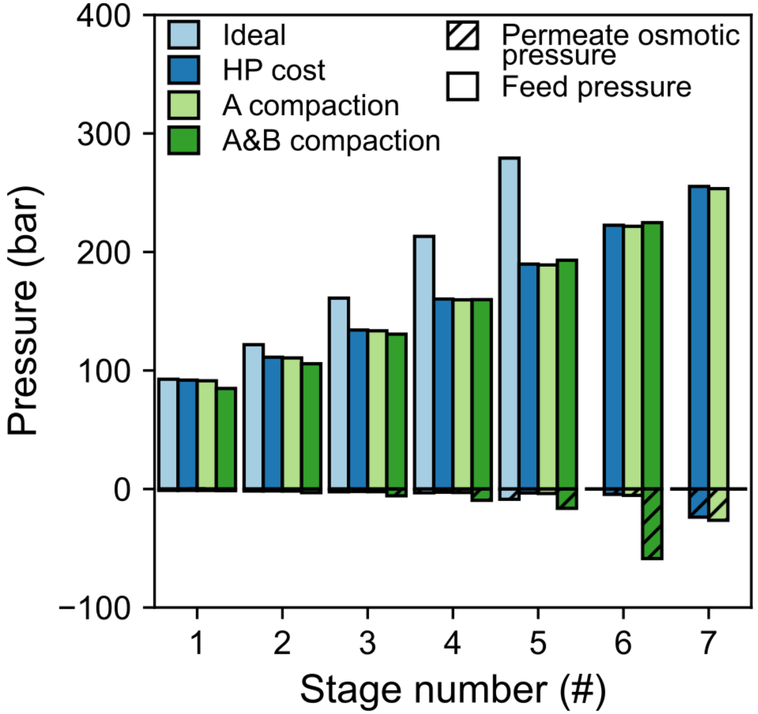
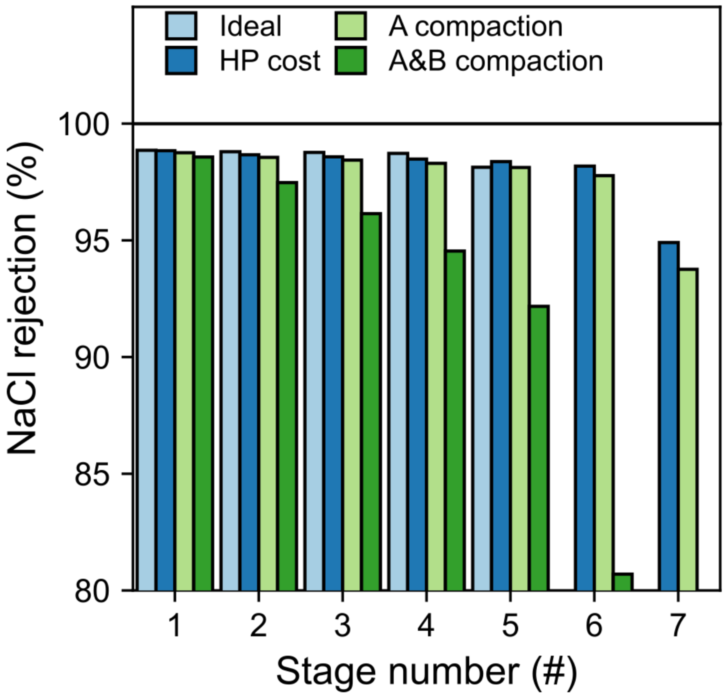
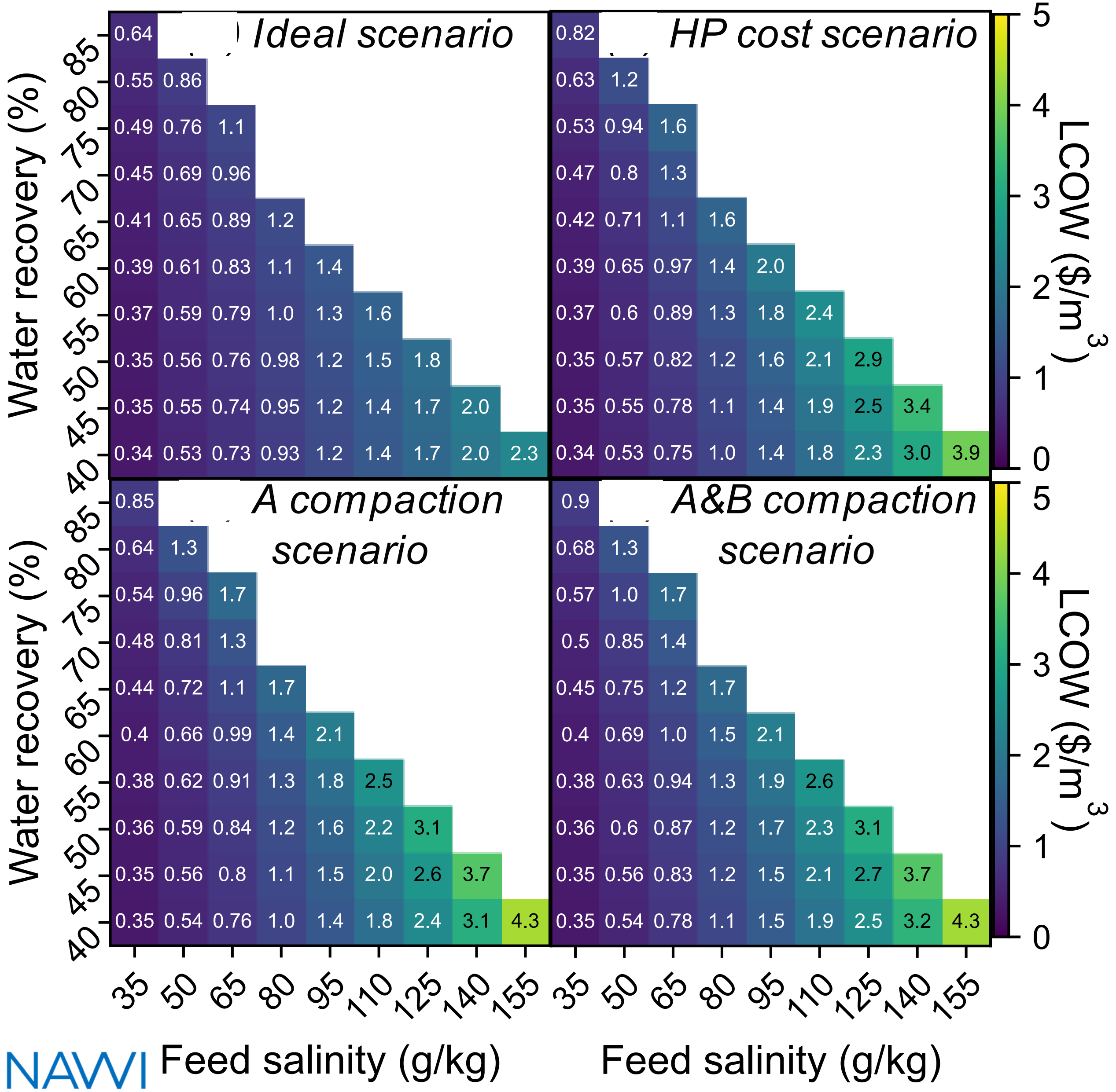








Exploring cost across broad range of conditions



1. Ideal scenario presents lowest cost of HPRO across all feed and water recovery cases
2. Including high pressure costs can nearly double process costs for high salinity cases
3. Membrane permeability (A) and salt rejection (B) loss increase costs by 5-10%

Changing process operation through reduced salt rejection and multi-staging mitigates impact of membrane compaction effects on cost

Under assumption that components, including membranes, don't catastrophically fail above 120 bar

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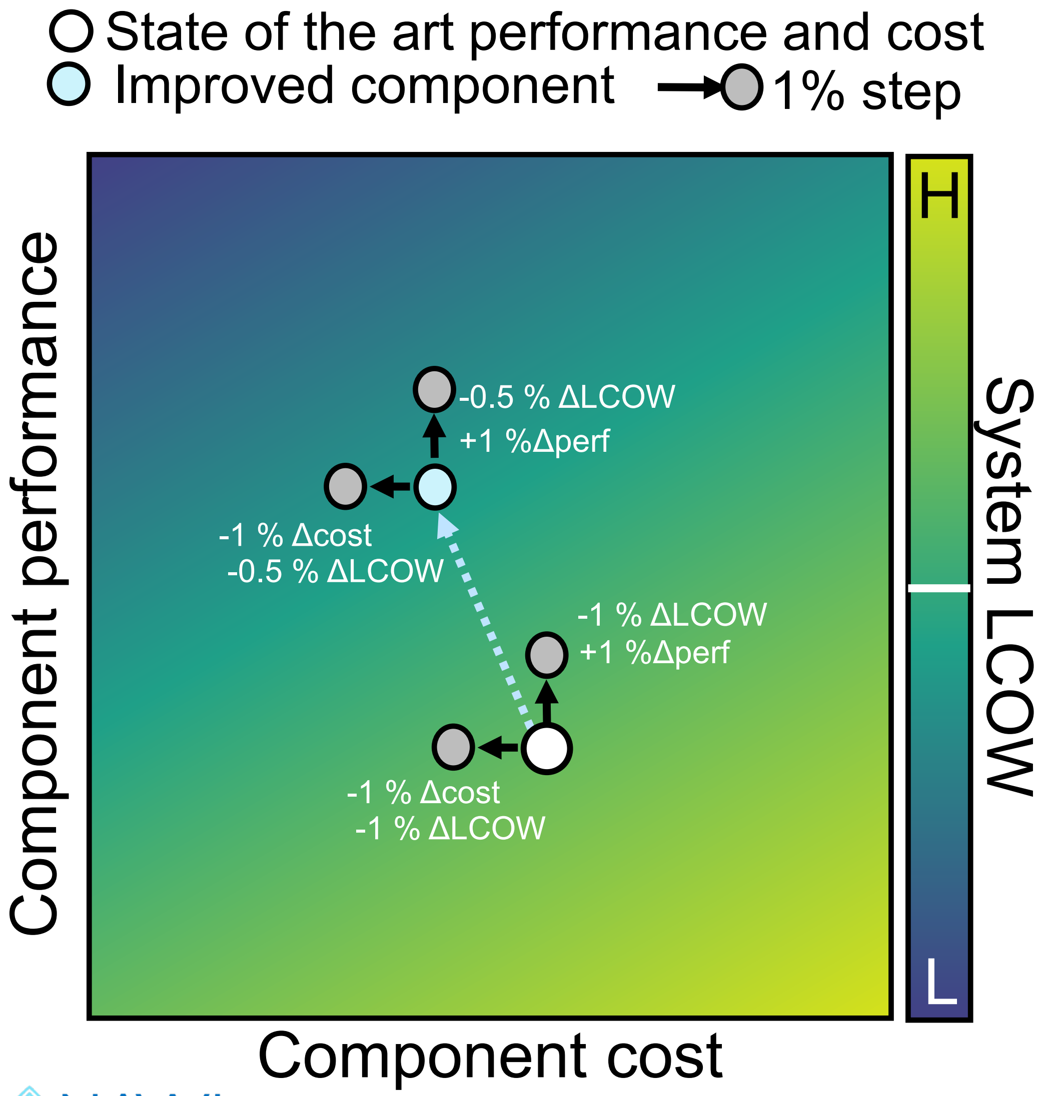
Assumptions in component performance can conceal value of innovation



Membrane performance
- Membrane water permeability (A)
- Compaction impact on A
- Membrane salt permeability (B)
- Compaction impact on B
- Membrane replacment rate

Module performance
- Mass transport rate multiplier
- Friction factor multiplier

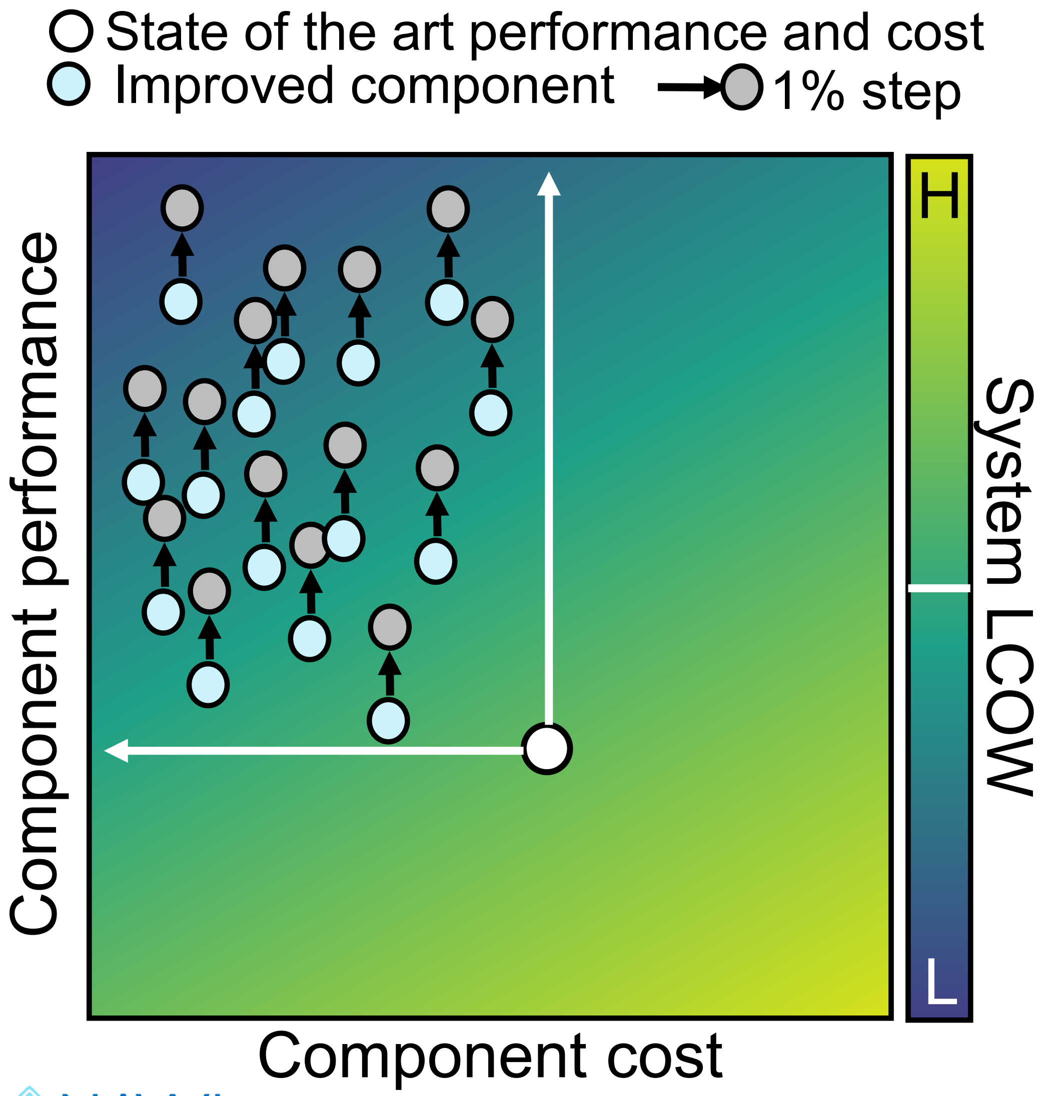
Pump & ERD performance
- Pump efficiency
- ERD efficiency

Cost
- Membrane cost
- Pressure vessel cost
- Cost pressure factor multiplier
- Electricity cost

Dudchenko, A. V., Bartholomew, T. V. & Mauter, M. S. High-impact innovations for high-salinity membrane desalination. *Proc Natl Acad Sci USA* **118**, e2022196118 (2021).

Stochastic value of innovation identifies innovations that will always reduce LCOW

VOI = % reduction in LCOW resulting from improving a single component by a %



Membrane performance

Membrane water permeability (A)

Compaction impact on A

Membrane salt permeability (B)

Compaction impact on B

Membrane replacment rate

Module performance

Mass transport rate multiplier

Friction factor multiplier

Pump & ERD performance

Pump efficiency

ERD efficiency

Cost

Membrane cost

Pressure vessel cost

Cost pressure factor multiplier

Electricity cost

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WaterTAP enables analysis of emerging brine management systems

Under assumption that components, including membranes, don’t catastrophically fail above 120 bar:

1. Loss of membrane permeability and salt rejection for current membranes can be mitigated through design changes and multi-staging
   - Research needs to focus on developing membranes that can retain their current performance over extended operating times (**3-5 years!**)
2. Multi-staging reduces operating costs by minimizing use of extreme pressure components
   - Investments should be made in developing pumps and membrane modules/PVs that operate at different pressures and have costs that scale with pressure

Acknowledgements and disclaimer

Contributors: Kurban Sitterley, Kinshuk Panda, Adam A. Atia, Ben Knueven, Timothy V. Bartholomew, and Meagan S. Mauter

Funding: *This material is based upon work supported by the National Alliance for Water Innovation (NAWI), funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Advanced Manufacturing Industrial Efficiency & Decarbonization Office (IEDO), under Funding Opportunity Announcement Number DE-FOA-0001905*

QUESTIONS

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Backup Slides

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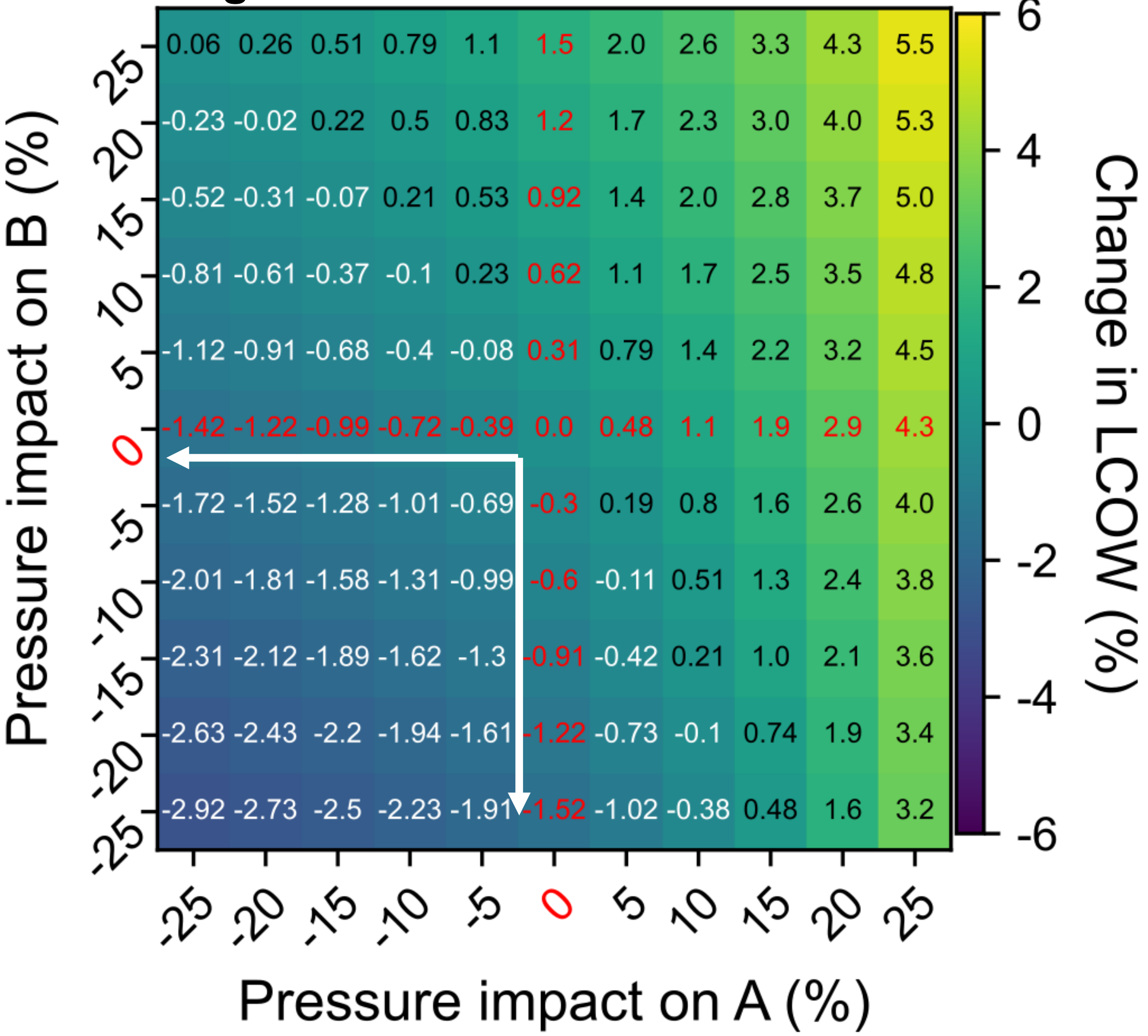
Dual parametric sweeps quantify sensitivity to selected parameters

65 g/L to 70% WR



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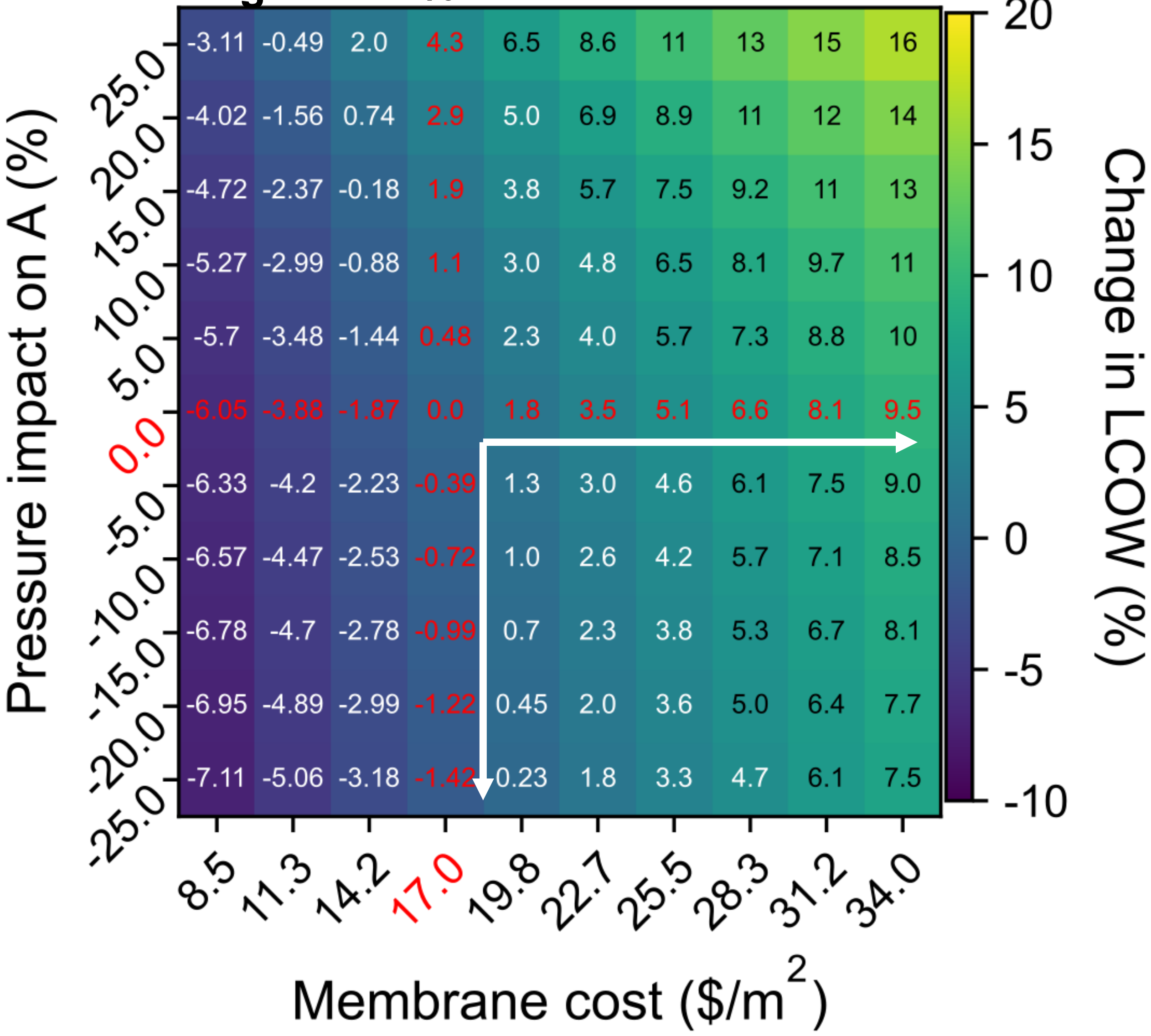

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