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Salinity gradient grid-scale energy storage with water production

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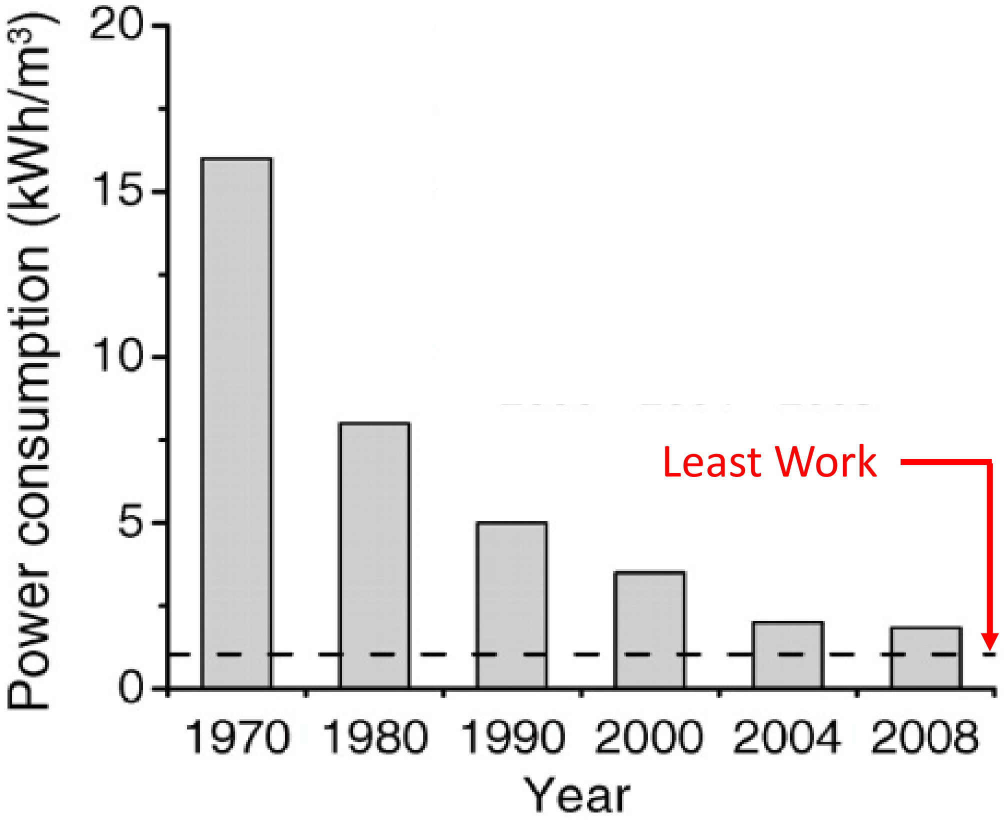
Outlook:

1. Motivation
2. Demand response technology
3. Demand response in reverse osmosis
4. Modelled configurations
5. Split reverse osmosis: Power demand variations
6. Demand response applied with electric utilities – Economic analysis
7. Conclusions

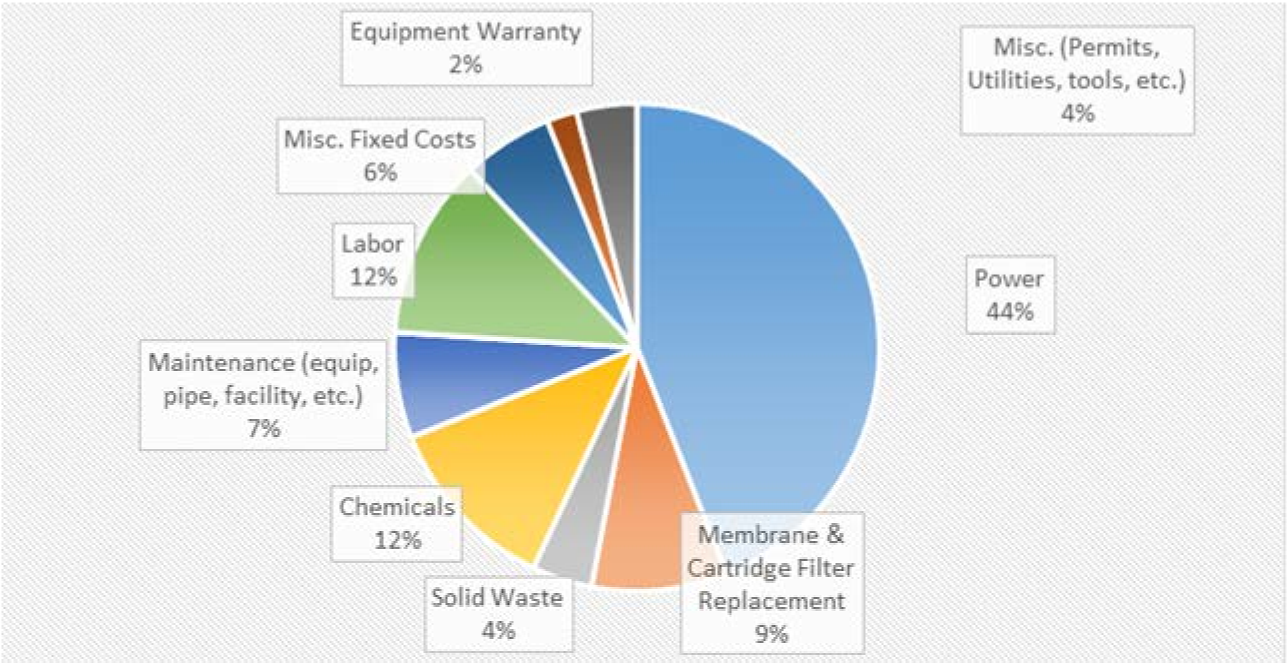
Seawater reverse osmosis energy consumption over time:

Change in power consumption for the reverse osmosis stage in *SWRO plants from the 1970s to 2008



Menachem, E, William A.P. (2011,August 05). Retrieved from https://science.sciencemag.org/content/333/6043/712

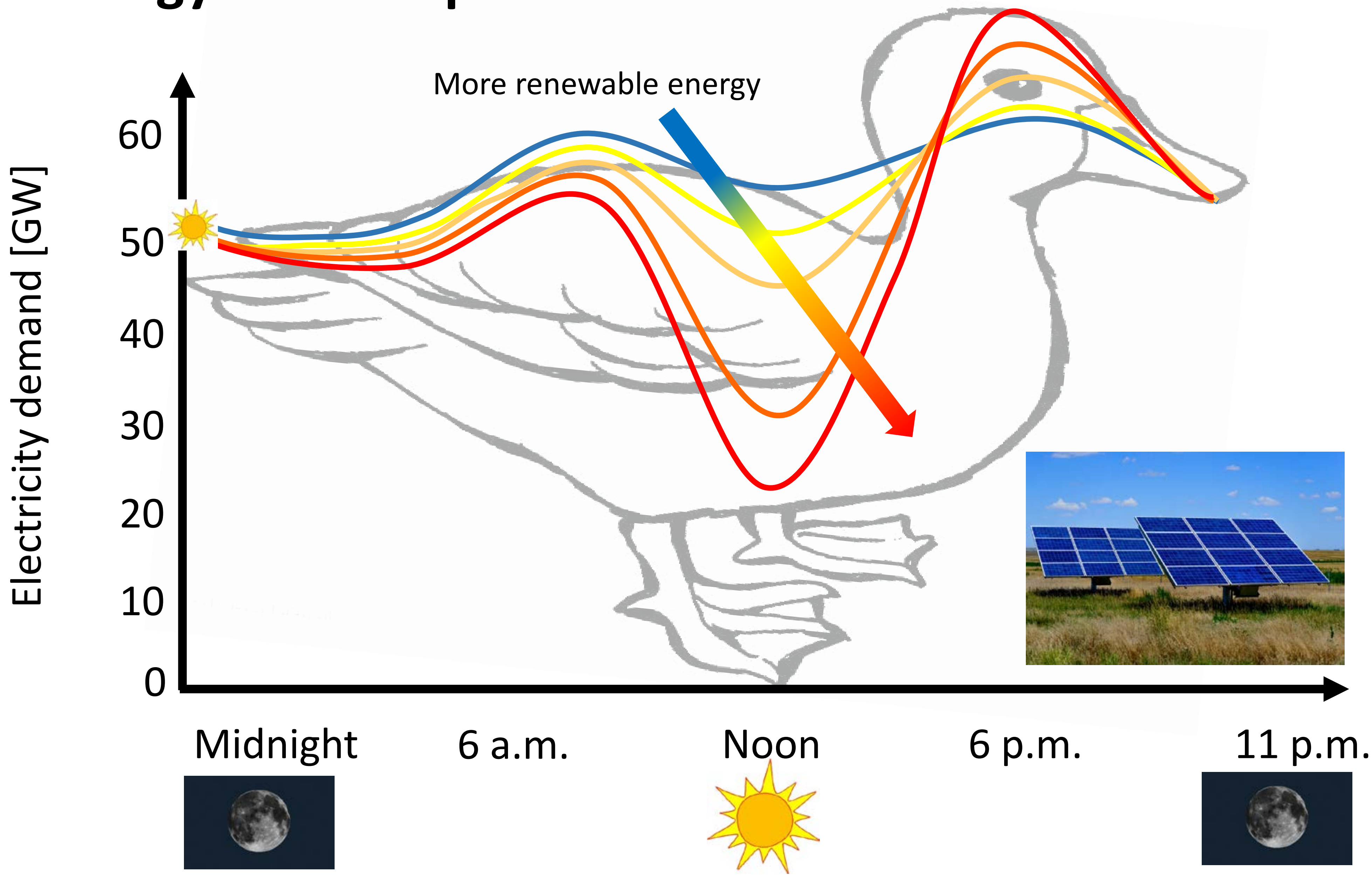
Typical *SWRO OPEX breakdown



Dhananjay, M. (2018, February 2015). Retrieved from: https://www.advisian.com/en-us/global-perspectives/the-cost-of-desalination

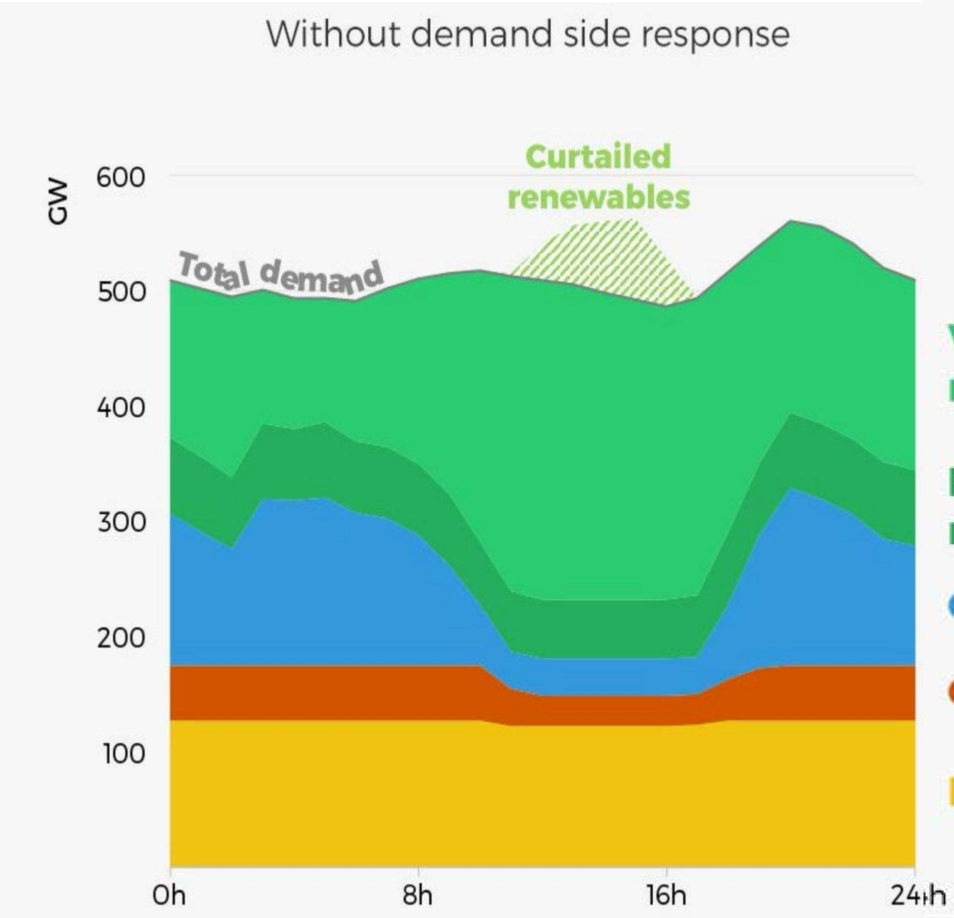
*SWRO: Sea Water Reverse Osmosis

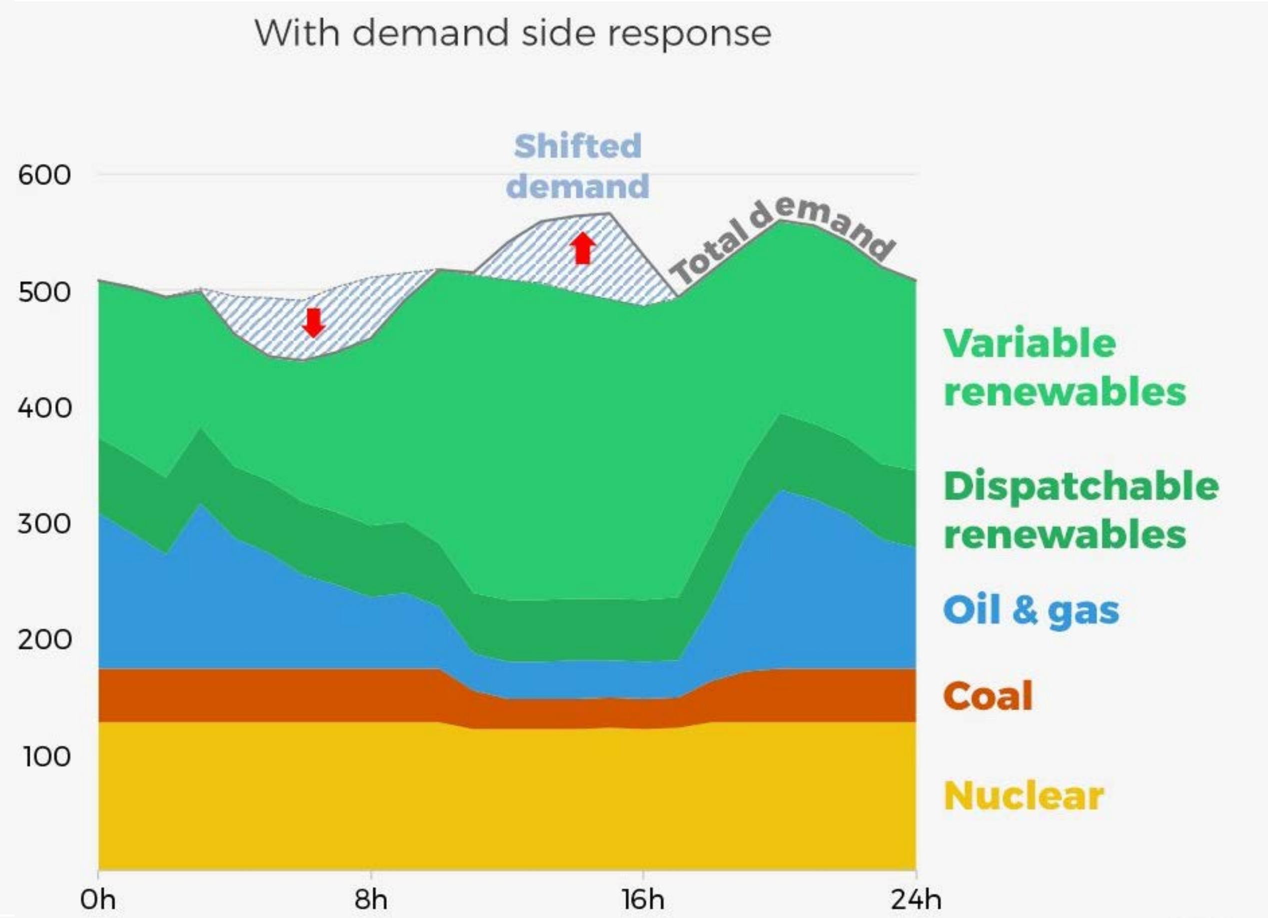
Energy demand profile:



- Add flexibility to the systems
- Shifting electricity usage during different periods of the day
- Energy storage

Demand response technology: Demand response (DR) can be defined as the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time.

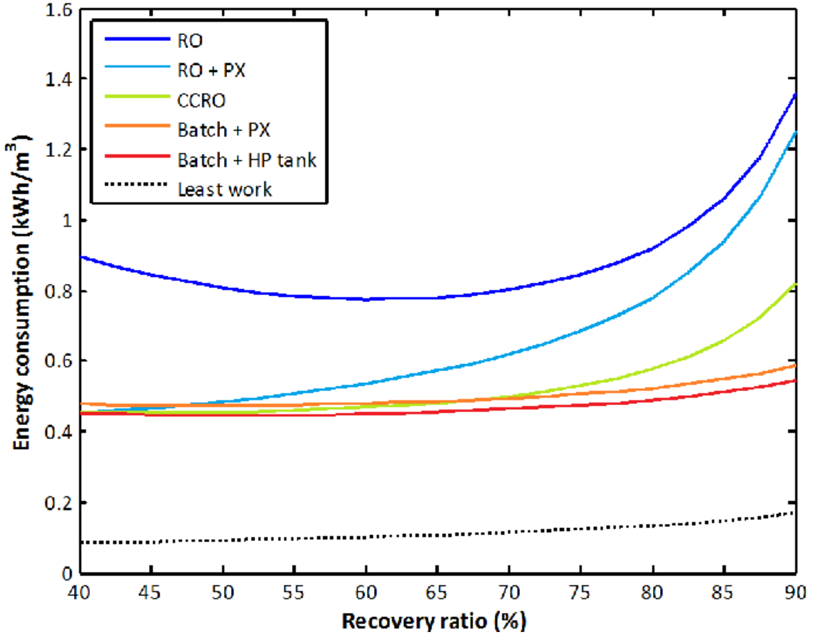




World Energy Outlook 2017, (2017, November 14)
https://www.iea.org/newsroom/energysnapshots/impact-of-demand-on-a-daily-load-curve.html

Demand response in reverse osmosis:

Energy consumption of continuous and time-variant RO configurations for various recovery ratios with 3 g/kg NaCl feed.



D. M. Warsinger et al., Water Research, vol. 106, pp. 272-282, 2016.

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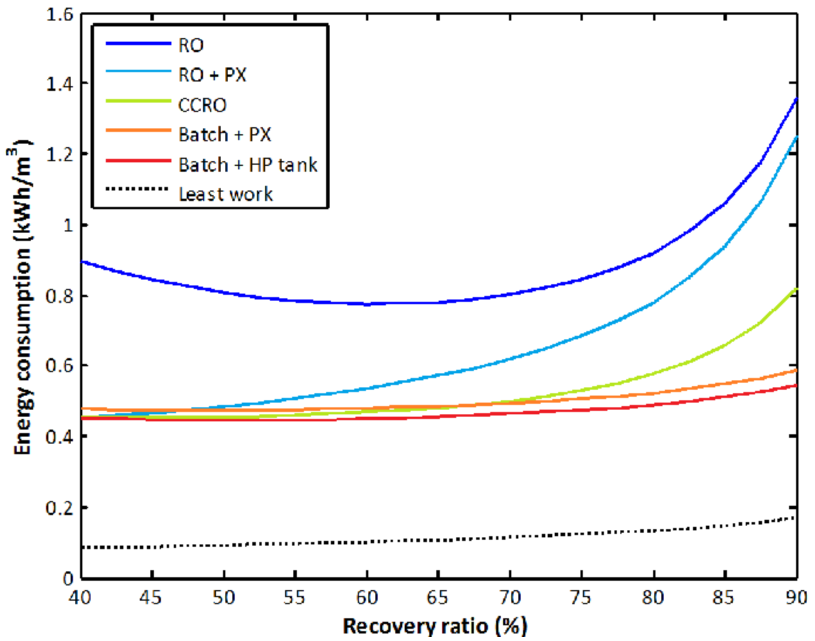

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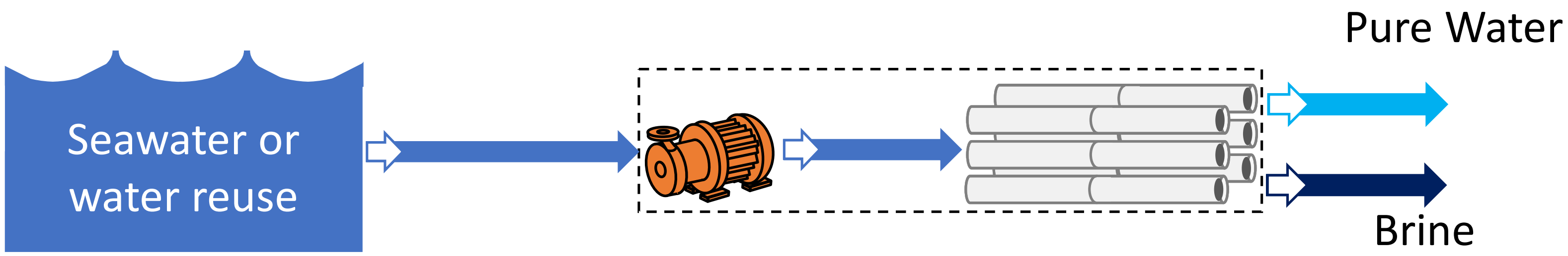

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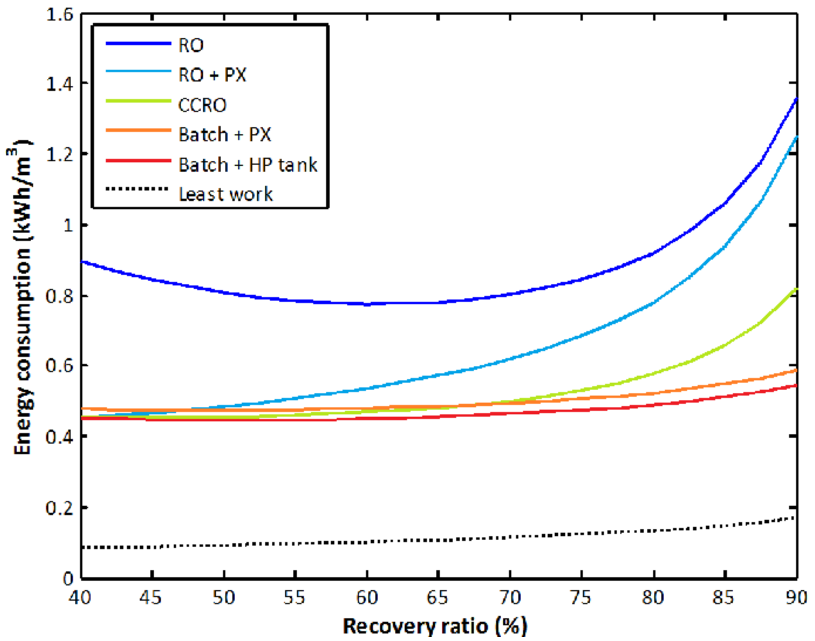

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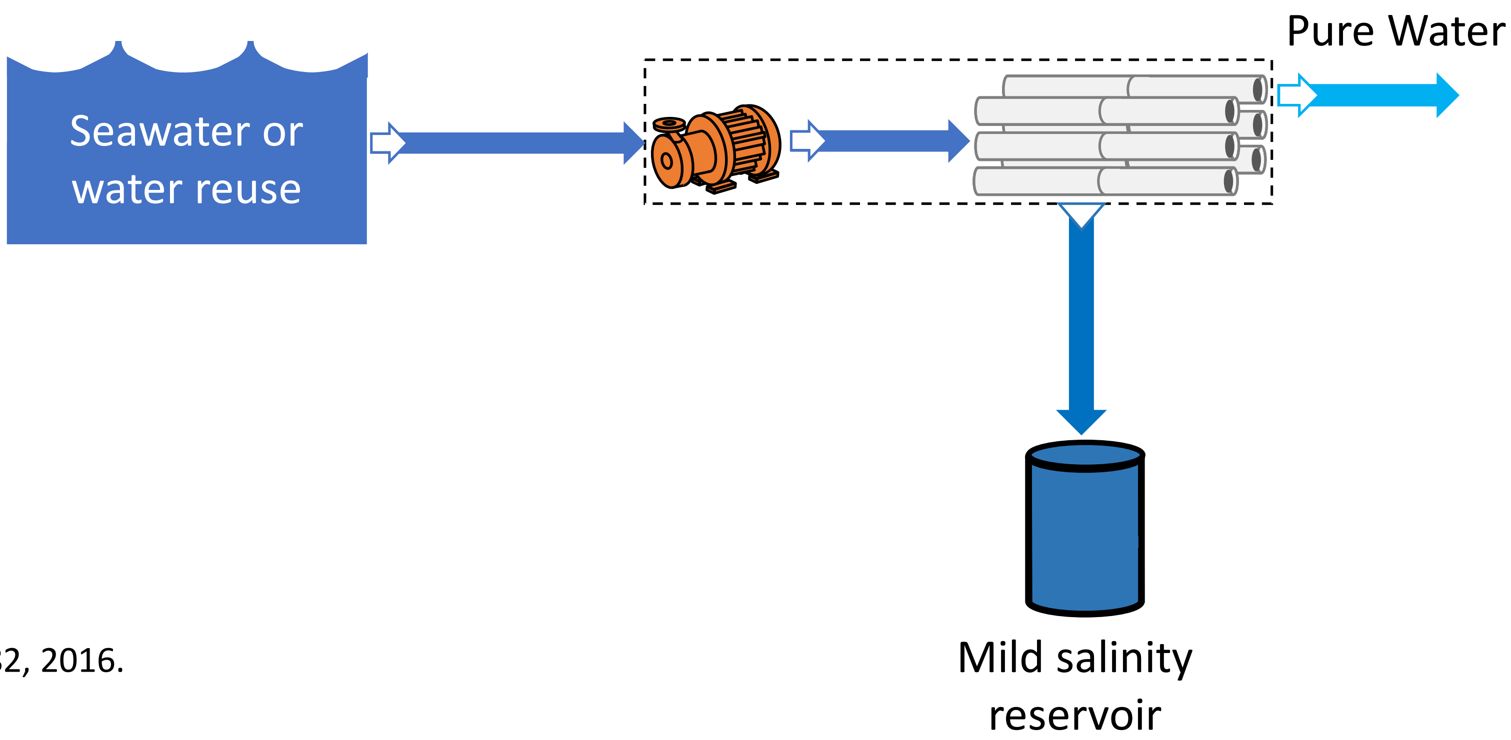

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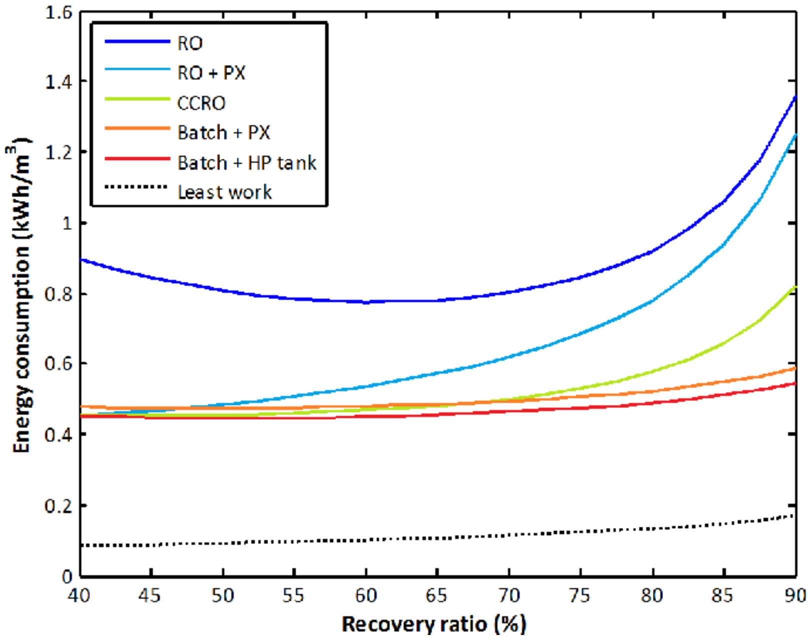
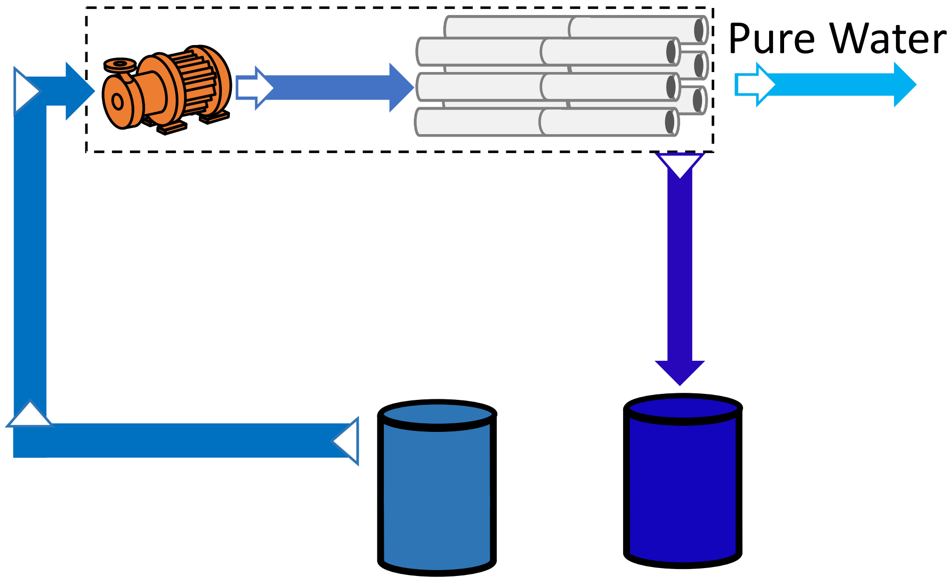


D. M. Warsinger et al., Water Research, vol. 106, pp. 272-282, 2016.



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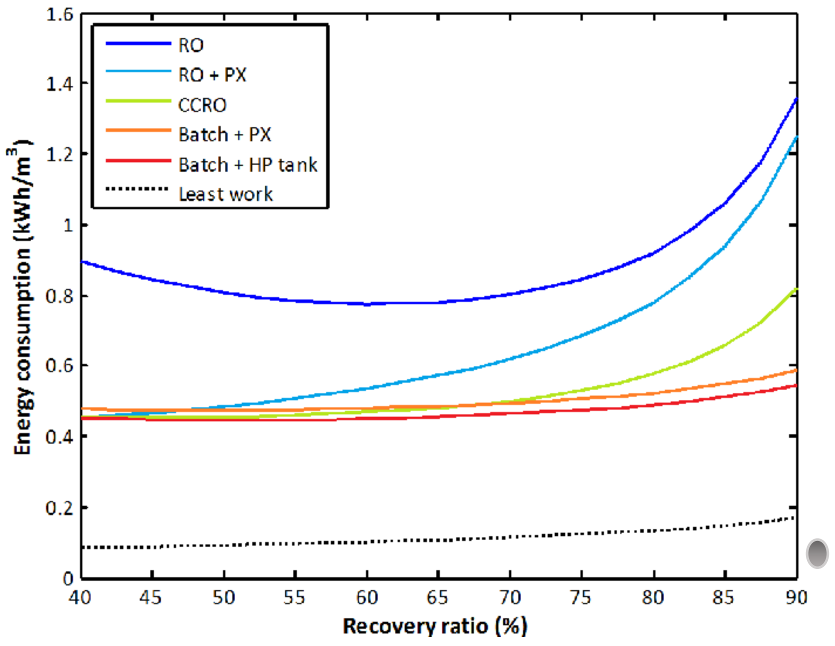
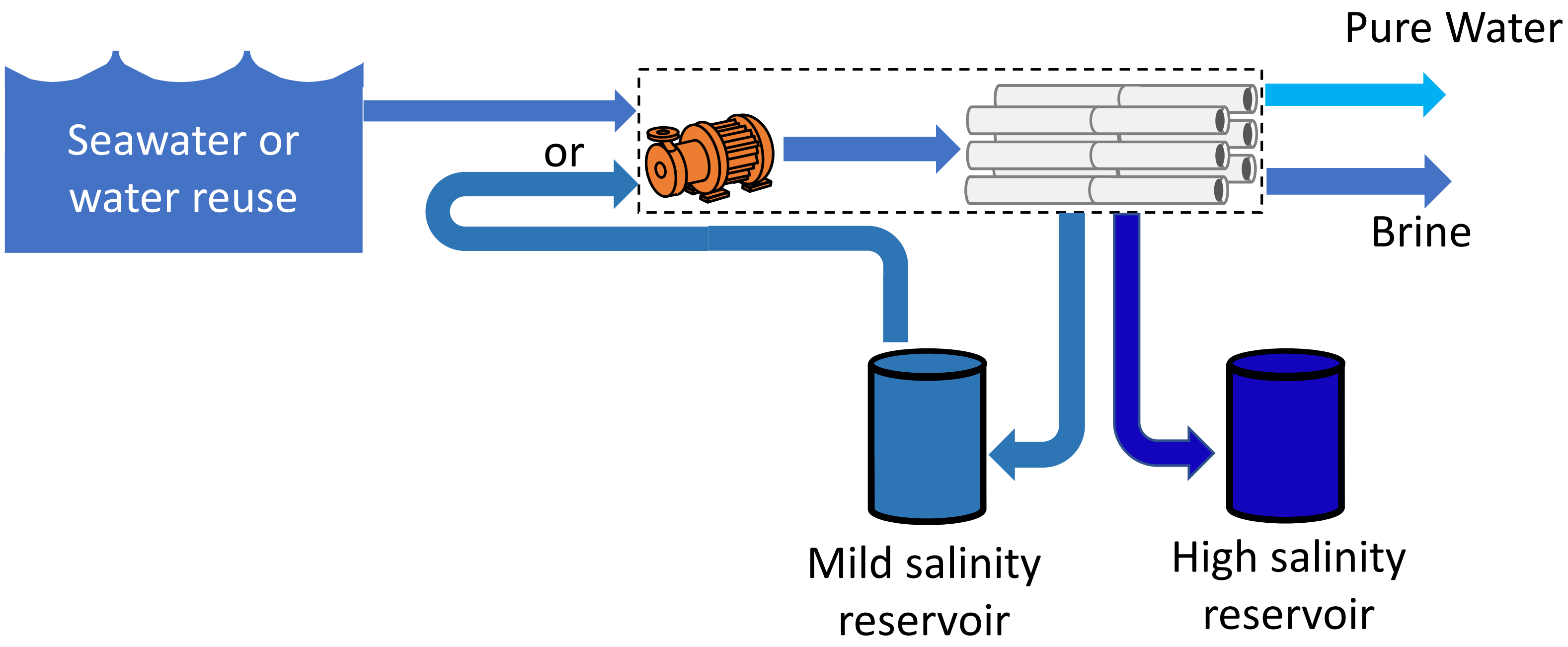


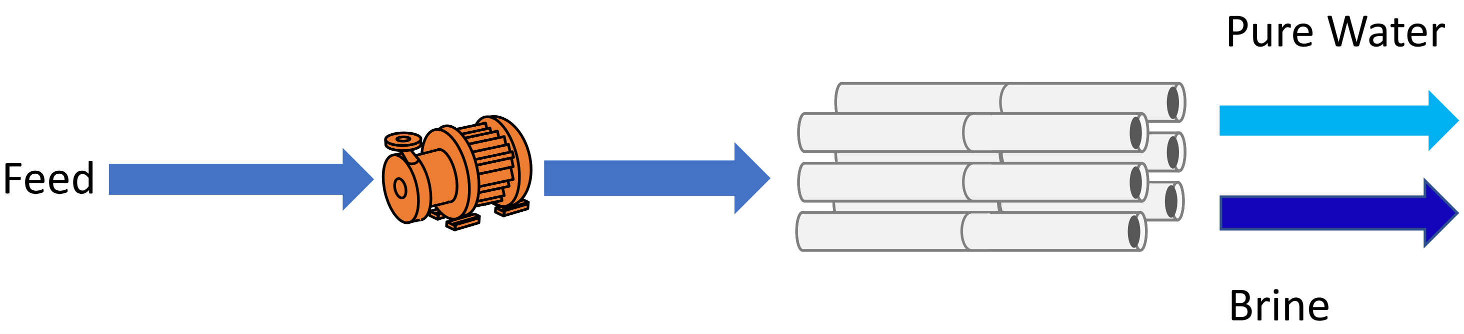
D. M. Warsinger et al., Water Research, vol. 106, pp. 272-282, 2016.



The plant can dramatically vary its energy needs and thus allow it to be a demand response-type system. When power is plentiful, it desalinates from medium to high salinity, if not, low to medium. Therefore the chemical potential from differences in salinity acts as the energy storage medium.

Modelled configurations:

Continuous reverse osmosis (RO)



$$W_{RO} = \frac{\pi_b + \Delta P_t + N\Delta P_l}{\eta_p RR}$$

Where:

W_{RO}: Specific energy consumption

π_b: Osmotic pressure

ΔP_t : Terminal overpressure

ΔP_l : Viscous losses each pass

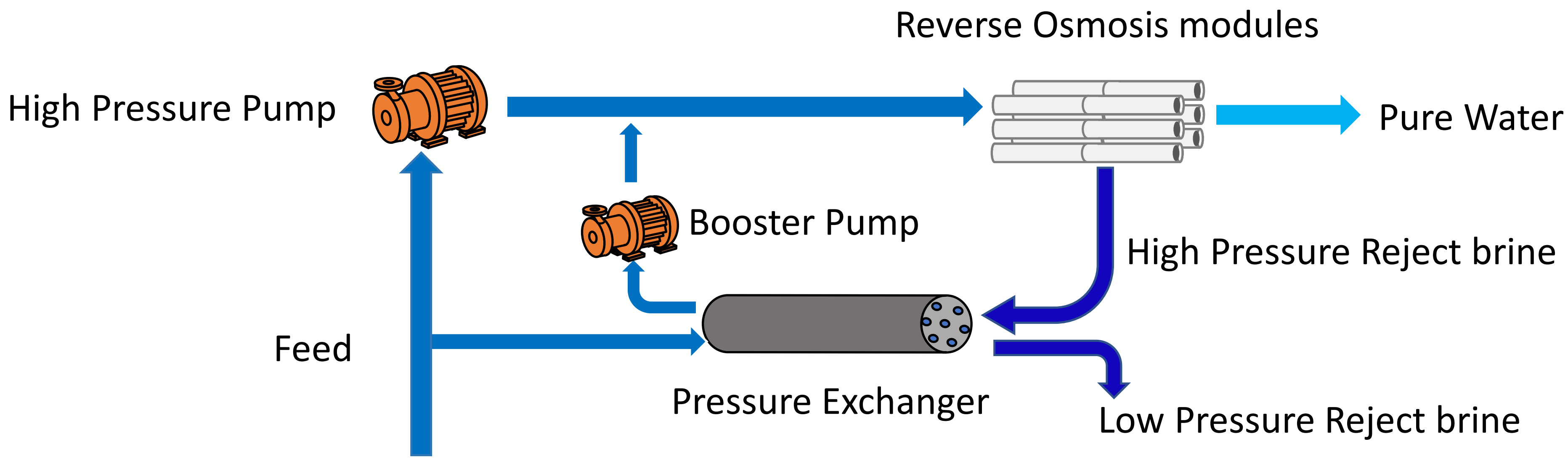
RR : Recovery ratio

η_p : Pump efficiency

N : Number of stages

Modelled configurations:

Continuous reverse osmosis + pressure exchanger (RO-PX)c



$$W_{RO} = \frac{\pi_b + \Delta P_t + N\Delta P_l}{\eta_p} + \frac{\left(\pi_b + \Delta P_t + N\Delta P_l - \eta_{px}[\pi_b + \Delta P_t]\right) * (1 - RR)}{RR\eta_b}$$

Where:

W_{RO}: Specific energy consumption

ΔP_t : Terminal overpressure

ΔP_l : Viscous losses each pass

RR : Recovery ratio

η_p : High pressure pump efficiency

η_{px} : Pressure exchanger efficiency

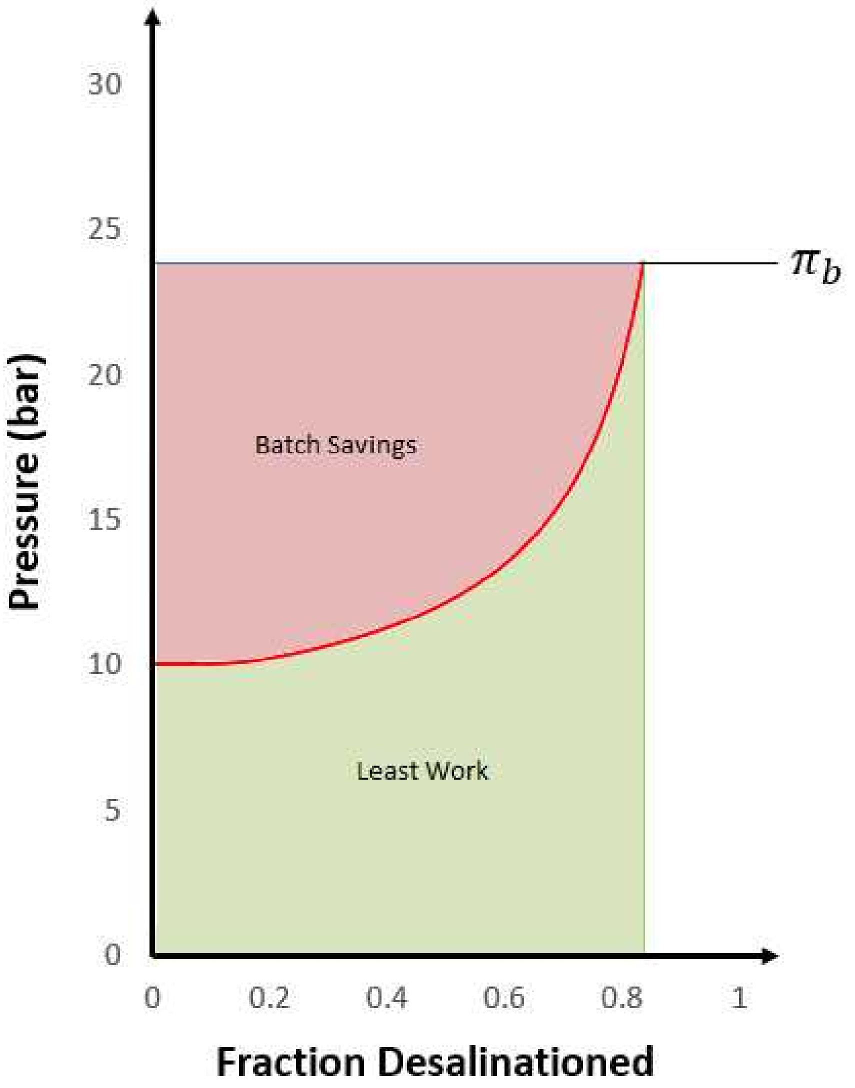
η_b : Booster pressure pump efficiency

π_b: Osmotic pressure

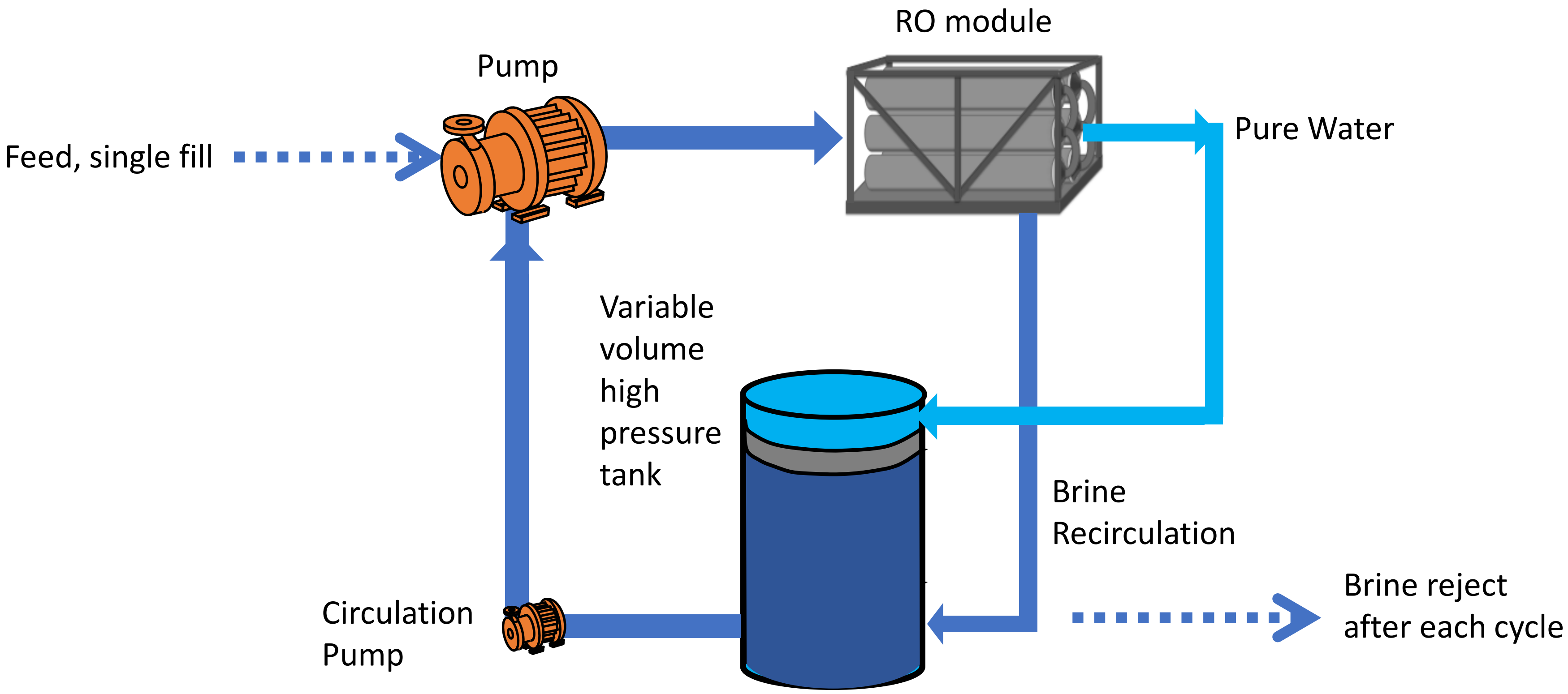
Modelled configurations:

Batch Reverse Osmosis:

Applied pressure vs RR for continuous and batch RO feed salinity: 3 [g/kg]



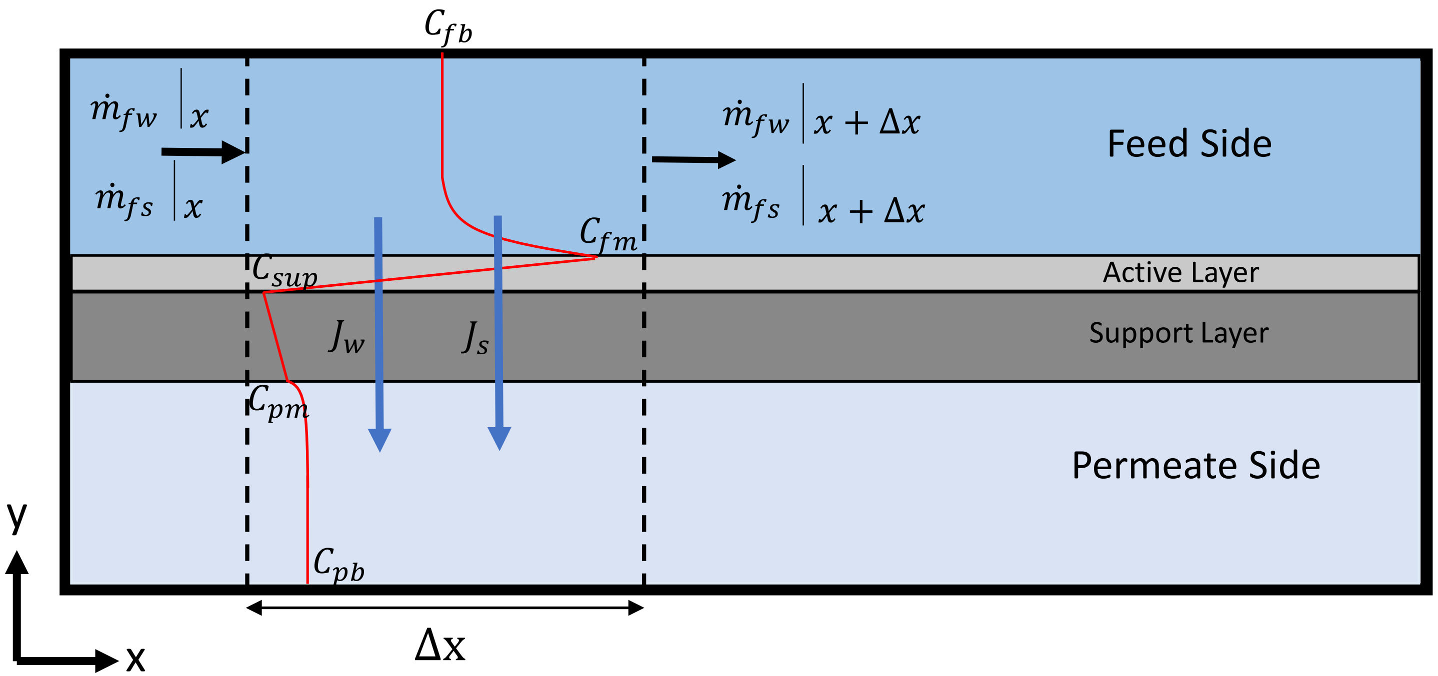
Batch RO: High Pressure Tank Concept



D. M. Warsinger[1], E. W. Tow[1], K. Nayar, and J. H. Lienhard V, "Energy efficiency of batch and semi-batch (CCRO) reverse osmosis desalination," *Water Research,* vol. 106, pp. 272-282, 2016.

D. M. Warsinger, E. W. Tow, R. McGovern, G. Thiel, and J. H. Lienhard V. Batch Pressure-Driven Membrane Separation with Closed-Flow Loop and Reservoir. *Full Patent Application, US non-provisional application No. 15/350,064 November 2016*

Modeled configurations: Batch reverse osmosis - modeling process



$$J_w = A(\Delta P - \Delta\pi)$$

$$\Delta C_m = C_{cm} - C_{sup}$$

$$\frac{\partial C\ (y)}{\partial t} + J_w \frac{\partial C\ (y)}{\partial y} = D\frac{\partial^2 C\ (y)}{\partial y^2}$$

$$J_s = B\Delta C_m$$

Where:

J_w: Water Flux

J_s: Salt Flux

ΔP: Pressure difference

$\Delta\pi$: Osmotic pressure difference

A: Membrane permeability Coefficient

B: Salt permeability Coefficient

C_{cb} : Bulk concentration in the feed side

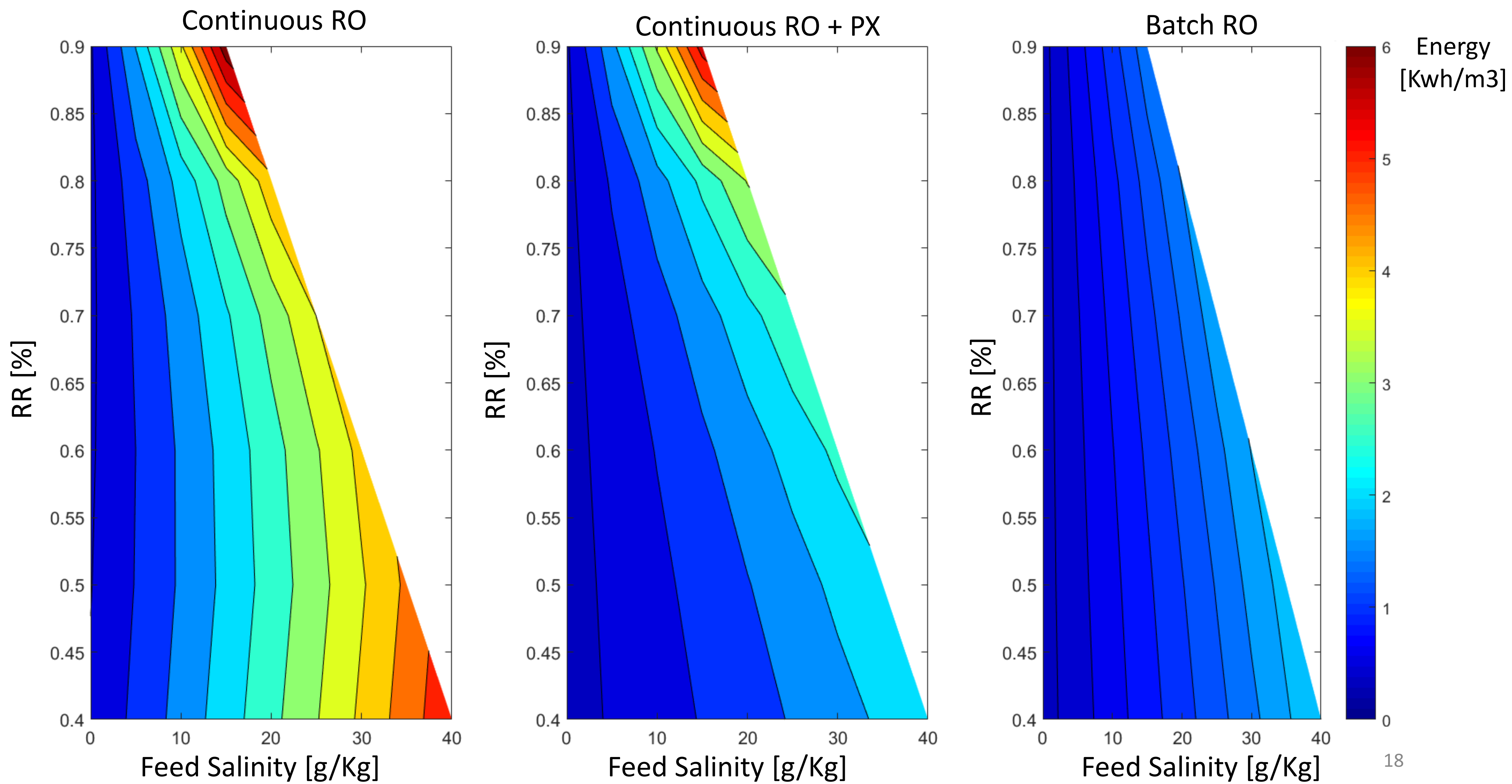
C_{cm} : Feed side concentration in the membrane

C_{sup} : Concentration in the support layer

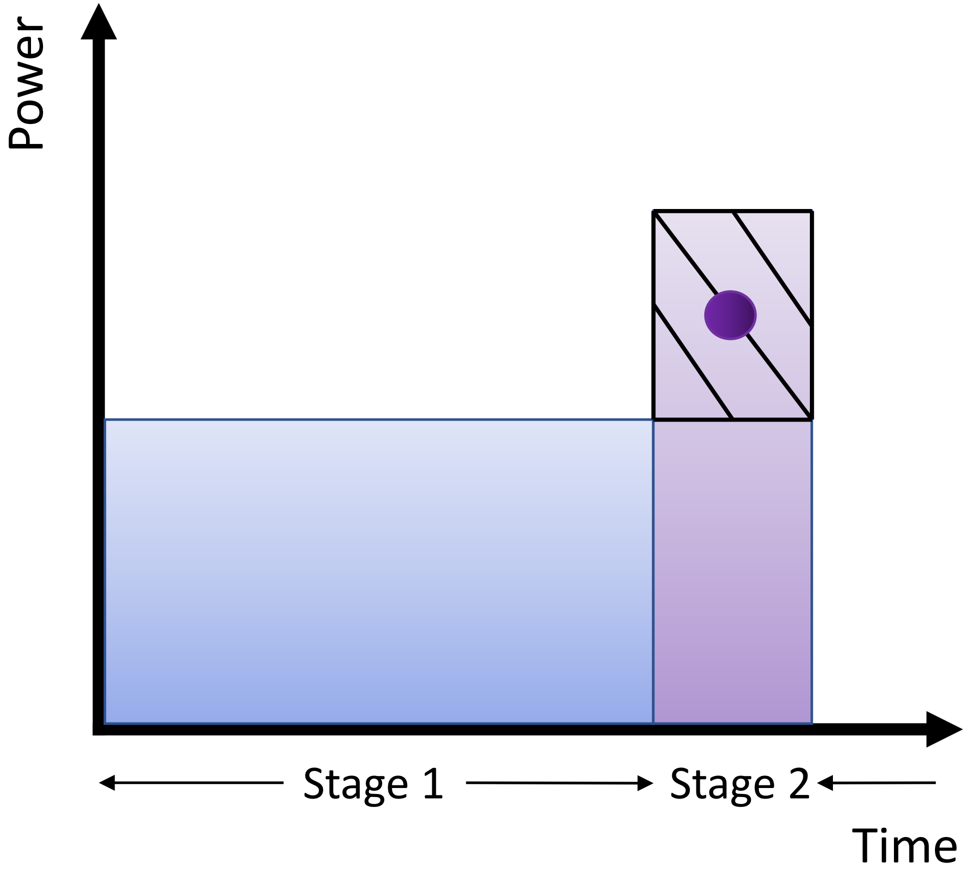
C_{dm} : Concentration in the membrane in the permeate side

C_{db} : Bulk concentration in the permeate side

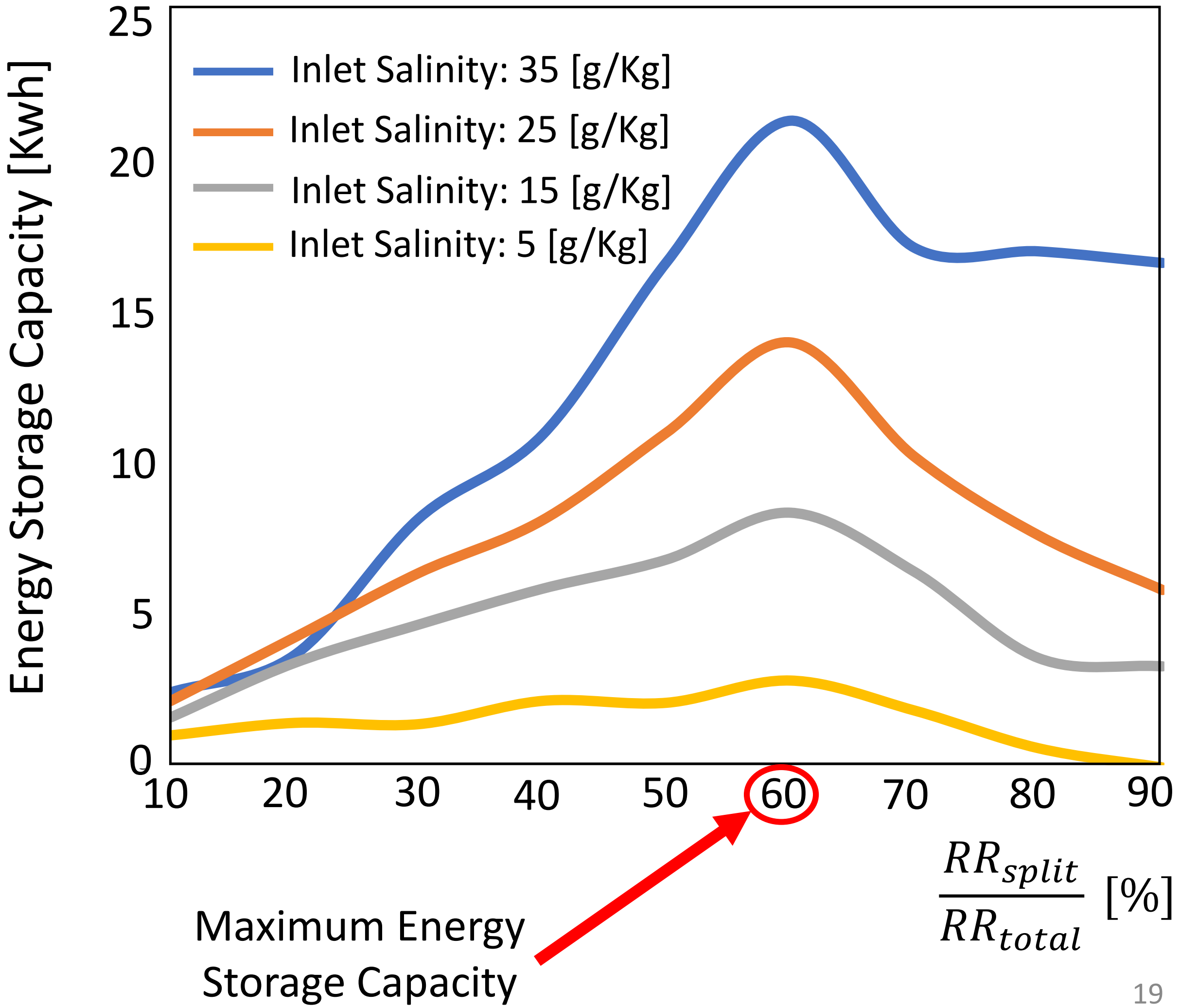
Reverse osmosis - model results: specific energy consumption



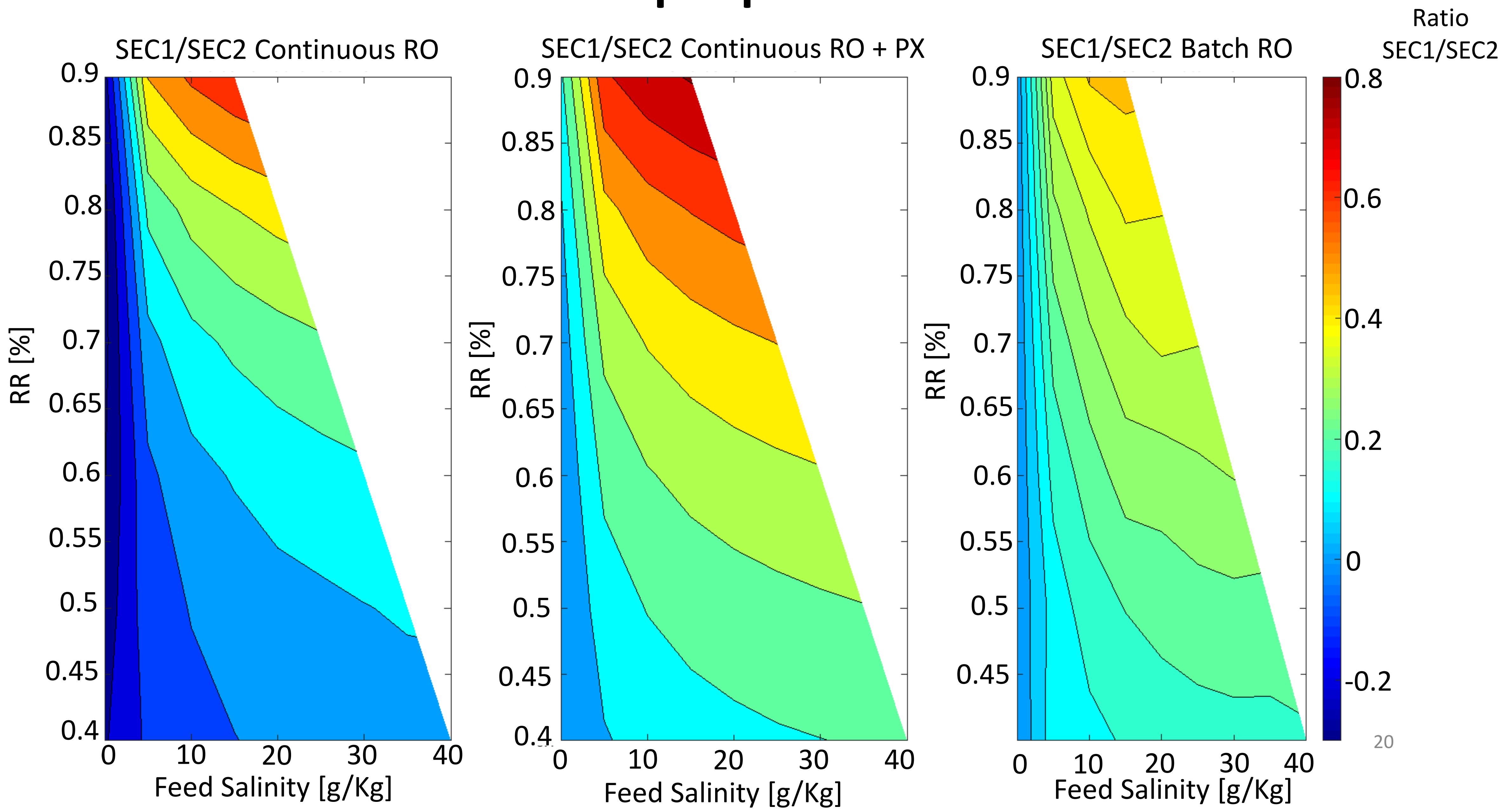
Reverse osmosis: split process



Energy storage Capacity vs ratio of RR



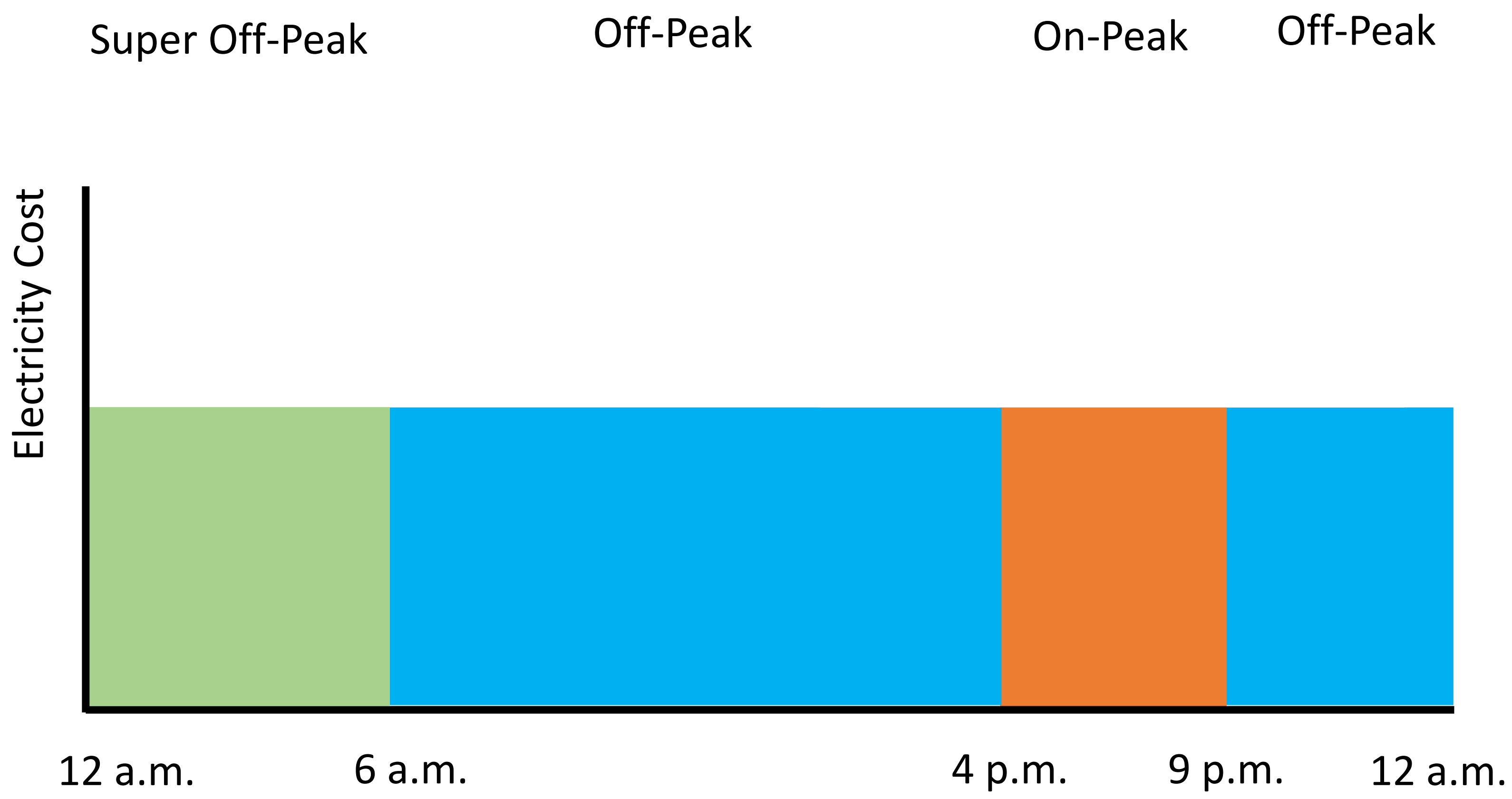
Power demand variations for split processes :



Demand response applied to electric utilities – Economic Analysis

Demand response programs

- Incentive based programs
  - Classical
  - Market based
- Price based programs
  - **Time of use (TOU)**
  - Critical peak pricing (CPP)
  - Extreme day CPP (ED-CPP)
  - Extreme day pricing (EDP)
  - Real time pricing (RTP)



Albadi, M.H., El-Saadany, E.F., 2007. Demand Response in Electricity Markets: An Overview. IEEE

Demand response applied to electric utilities – Economic analysis

Case 1: **Sea Water**

Feed Salinity: 35 [g/Kg]

Final RR: 50 %

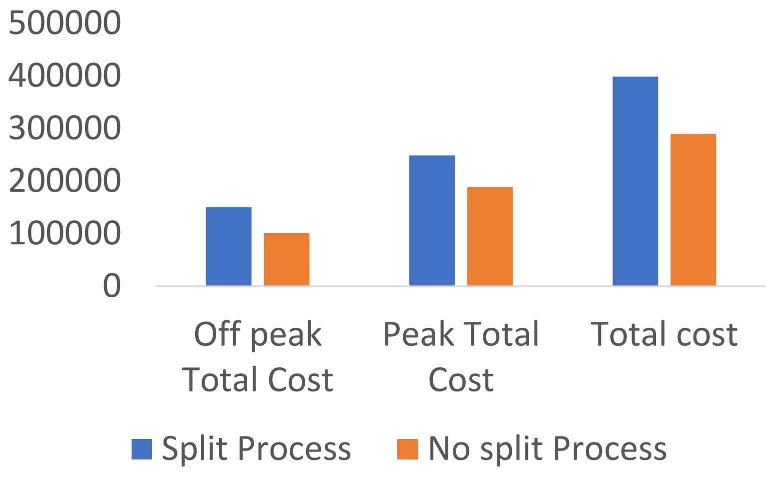
Plant Capacity: 200000 $[m^3/day]$

Off-peak price: 0.22 [usd/Kwh]

On-peak price: 0.41 [usd/Kwh]

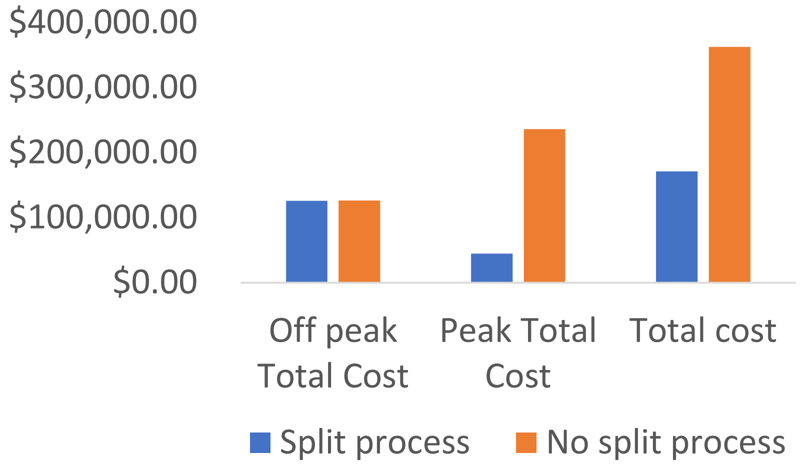
Off-Peak time = 12 [hours]

Continuous RO



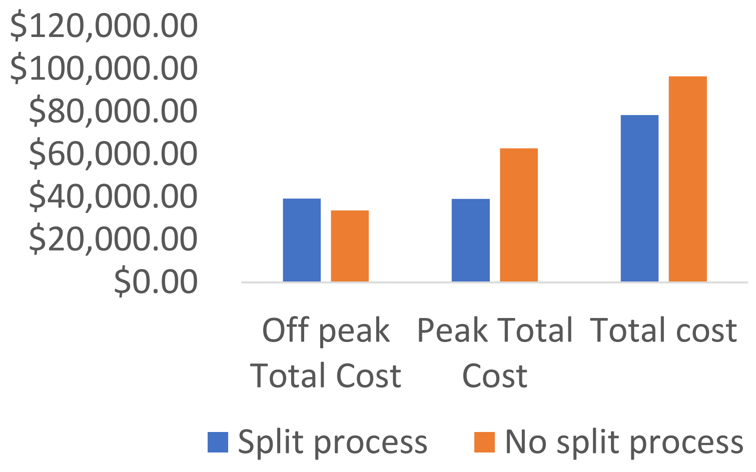
Energy cost difference: -37%

Continuous RO + PX



Energy cost difference: 17%

Batch RO



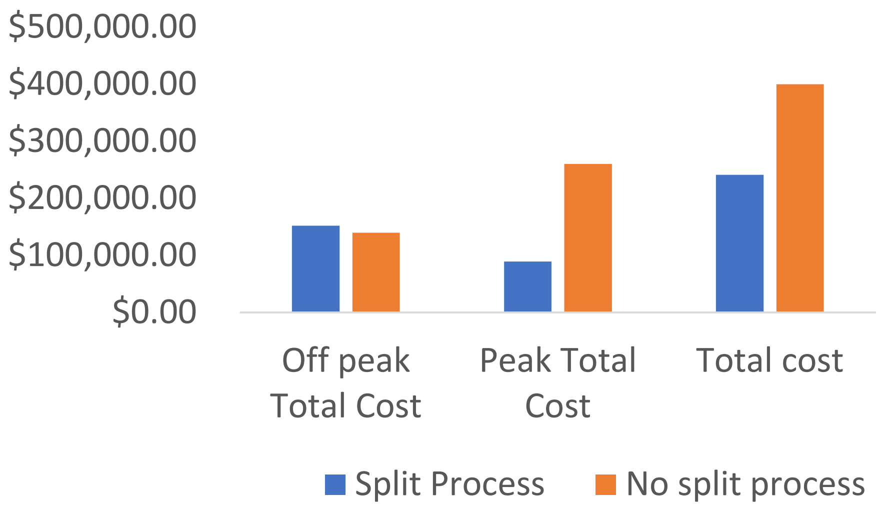
Energy cost difference: 6 %

Demand response applied to electric utilities – Economic analysis

Case 2: **Brackish Water**
Feed Salinity: 15 [g/Kg]
Final RR: 90 %

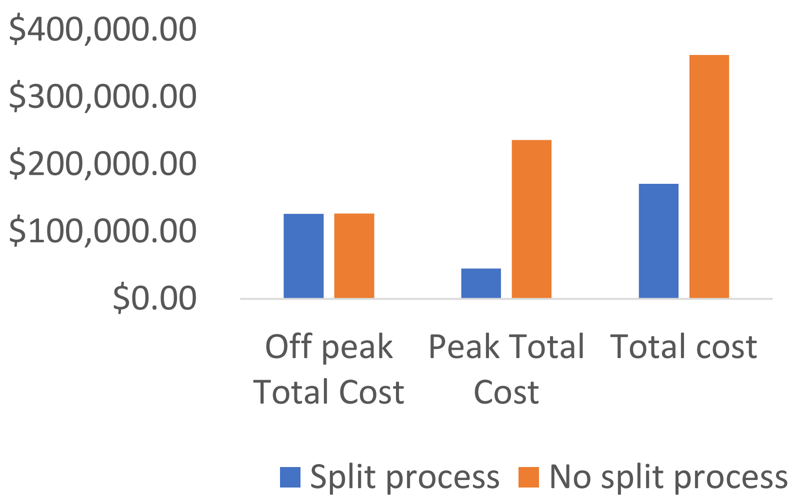
Plant Capacity: 200000 $[m^3/day]$
Off-peak price: 0.22 [usd/Kwh]
On-peak price: 0.41 [usd/Kwh]
Off-Peak time = 12 [hours]

Continuous RO



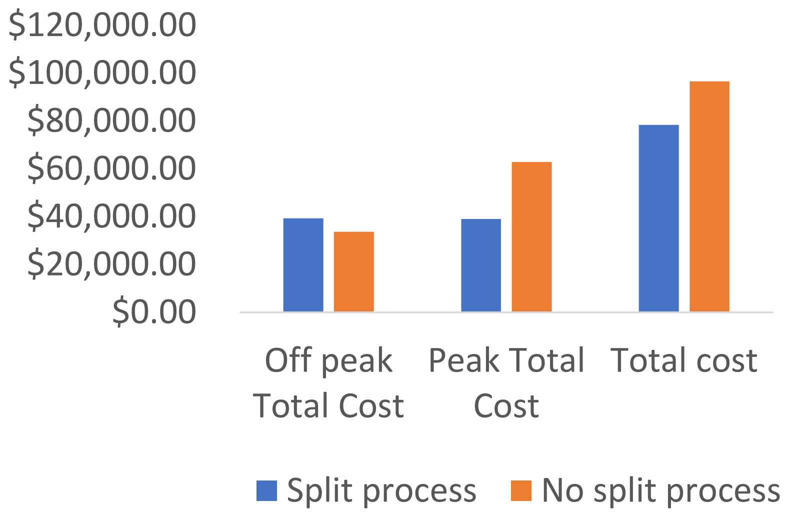
Energy cost difference: 39%

Continuous RO + PX



Energy cost difference: 52%

Batch RO



Energy cost difference: 18%

Conclusions:

- Reverse osmosis technology may turn into a demand-response type of process by splitting it in different stages.

- The configuration where the continuous reverse osmosis is paired with a pressure exchanger stands out as the variation where the highest energy variations may be obtained.

- The ability of changing the power demand in the reverse osmosis plants allows its integration with different sources of renewable energies.

References:

Warsinger, D.M., Tow, E.W., Nayar, K.G., Maswadeh, L.A., Lienhard V, J.H., 2016. Energy efficiency of batch and semi-batch (CCRO) reverse osmosis desalination. Water Research , vol. 106, pp. 272-282.

Wei, Quantum J. et al. "Batch reverse osmosis: experimental results, model validation and design implications." 2019 AMTA/ AWWA Membrane Technology Conference & Exposition, February 2019 2019, New Orleans, Louisiana, American Membrane Technology Association, February 2019.

Albadi, M.H., El-Saadany, E.F., 2007. Demand Response in Electricity Markets: An Overview. IEEE

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FULBRIGHT Colombia