PRODUCED WATER SOCIETY 2023

Optimal Desalination Technologies for Produced Water Networks

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Carnegie Mellon

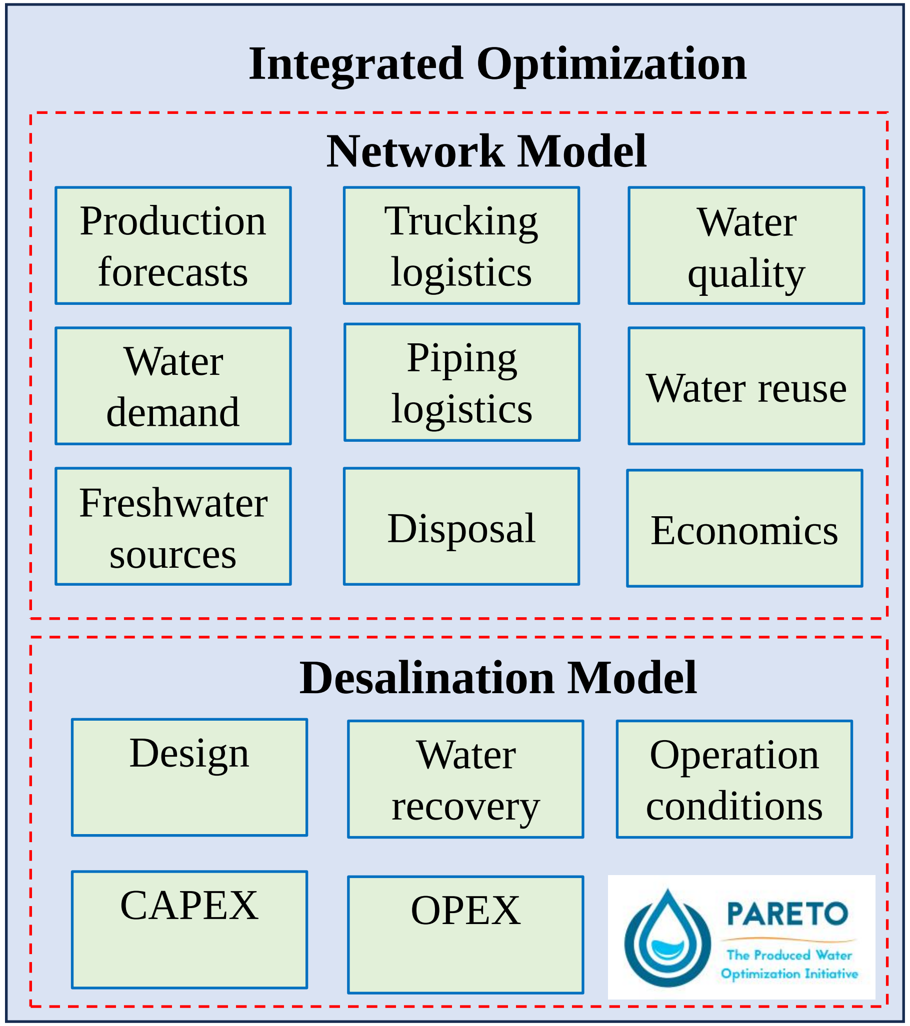
PARETO

The Produced Water Optimization Initiative

Outline

1. Project summary
2. Motivation
3. Desalination technologies for produced water
4. Optimization of desalination units
5. Integrating desalination into a produced water network
6. Optimization of the integrated system
7. Insights on disposal vs desalination tradeoff
8. Conclusions and future work

Project Summary



User Inputs:

- Infrastructure and water quantity and quality forecast

Objectives:

- Build framework for cost estimation of desalination units
- Integrate desalination units into produced water network framework in PARETO for optimal and sustainable water management

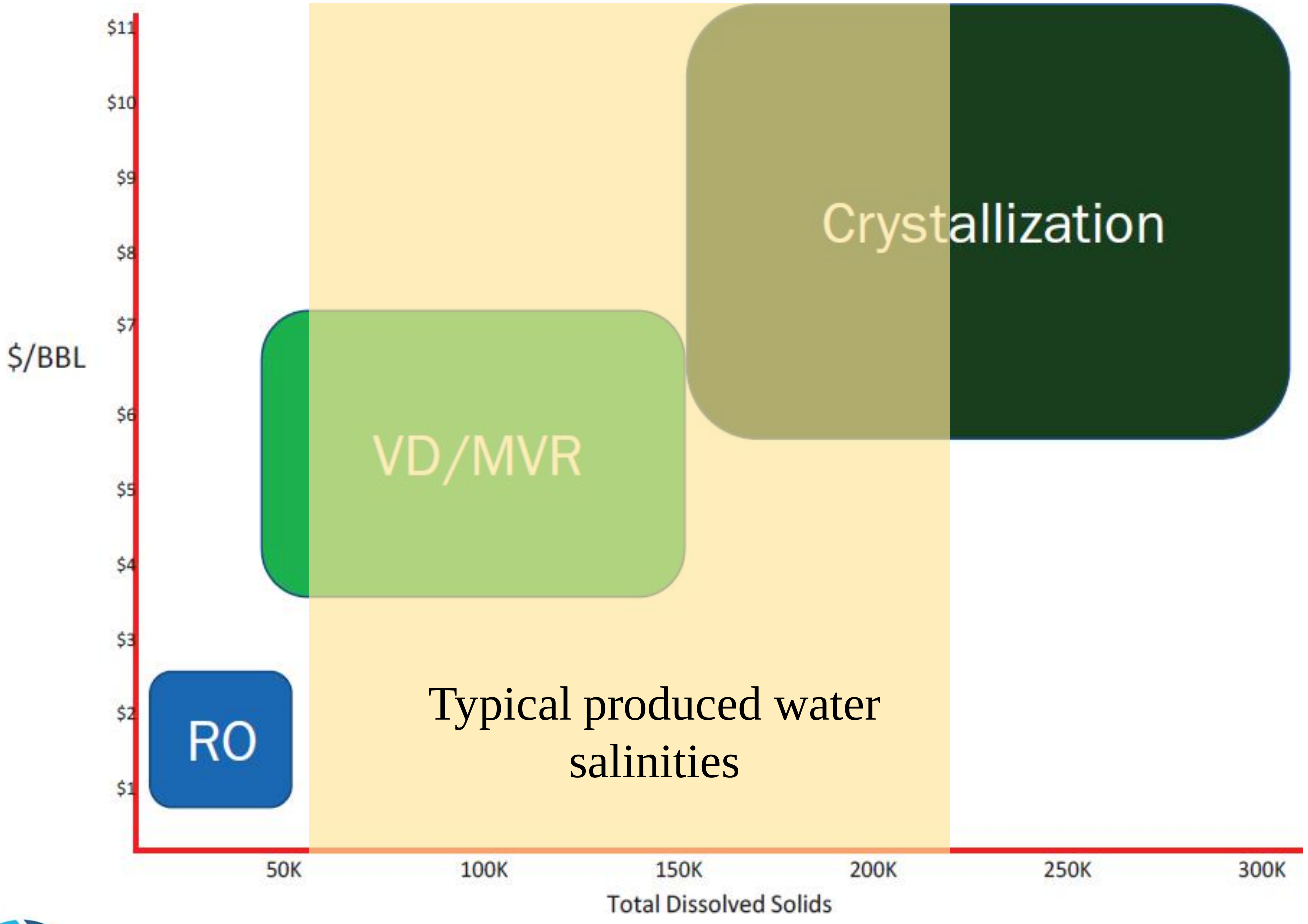
Key Conclusions:

- Desalination design and operation decisions can be made in sync with operation of the network
- This framework informs users with flows and salinity to desalination unit and generates operation policy for each period in the horizon

WHAT TECHNOLOGIES?
HOW EXPENSIVE?
OPTIMAL DESIGN AND OPERATION?

A stock pond south of Dallas dries up due to drought conditions. Across Texas, drought is taxing reservoirs and rivers and groundwater aquifers are being pumped faster than they can recharge

Desalination Technologies



<u>Mechanical vapor recompression</u>

1. Handles high salinity
2. Well established at industrial scale
3. Requires less pre-treatment than for membrane-based processes
4. Less susceptible to fouling due to oil and grease

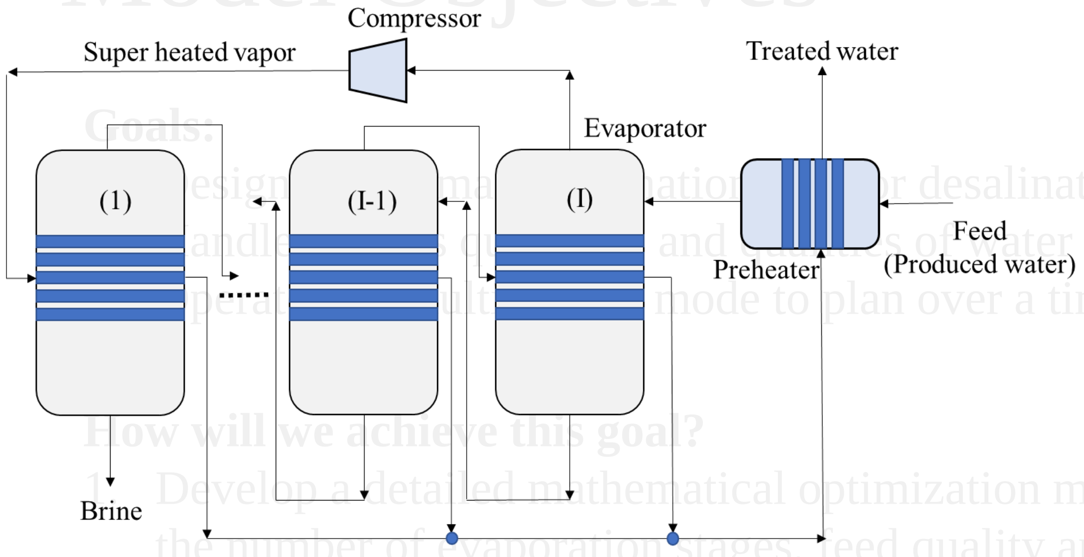
Model Objectives

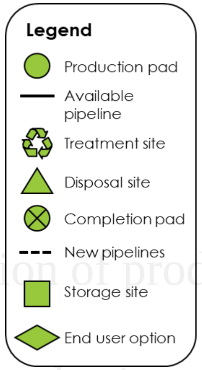
Goals:

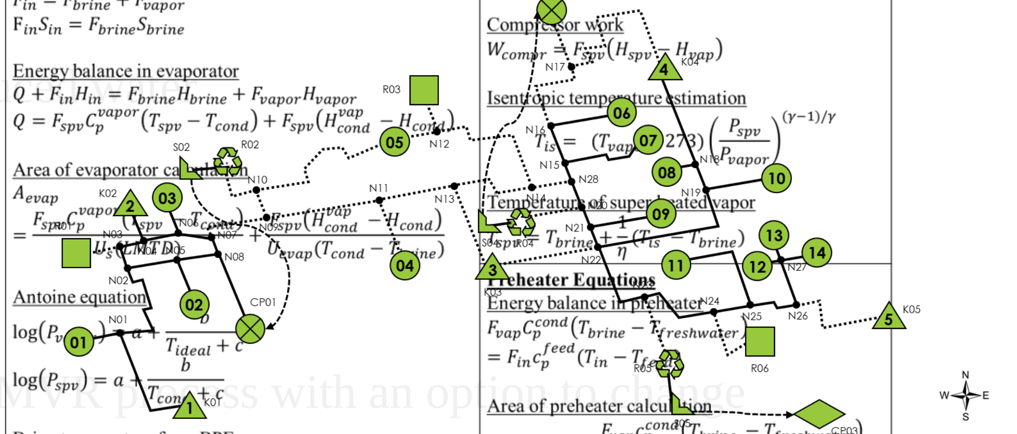
- Design ... for desalination of produced water
- Handle ... quality and quantities of water
- Operate ... mode to plan over a time horizon

How will we achieve this goal?

1. Develop a detailed mathematical optimization model of the MVR process with an option to change the number of evaporation stages, feed quality and quantity
2. Define economic (cost minimization) or environmental (max reuse/treatment) objectives
3. Integrate the detailed model into the network models developed in PARETO to help make optimal design and operation decisions







min TAC

$TAC = CAPEX_{ann} + OPEX_{ann}$

Evaporator Equations

Mass balance in evaporator

$F_{in} = F_{brine} + F_{vapor}$

$F_{in}S_{in} = F_{brine}S_{brine}$

Energy balance in evaporator

$Q + F_{in}H_{in} = F_{brine}H_{brine} + F_{vapor}H_{vapor}$

$Q = F_{spv}C_p^{vapor}(T_{spv} - T_{cond}) + F_{spv}(H_{cond}^{vap} - H_{cond})$

Area of evaporator calculation

$A_{evap} = \frac{F_{spv}C_p^{vapor}(T_{spv} - T_{cond})}{U_s(LMTD)} + \frac{F_{spv}(H_{cond}^{vap} - H_{cond})}{U_{evap}(T_{cond} - T_{brine})}$

Antoine equation

$\log(P_v) = a + \frac{b}{T_{ideal} + c}$

$\log(P_{spv}) = a + \frac{b}{T_{cond} + c}$

Brine temperature from BPE

$T_{brine} = T_{ideal} + BPE$

LMTD for evaporator

$LMTD = (0.5\,\theta_1\,\theta_2(\theta_1 + \theta_2))^{1/3}$

Bounds for Feasible Operation

$T_{spv} \geq T_{cond} + \Delta T_{min}^{(1)}$

$T_{brine} \geq T_{in} + \Delta T_{min}^{(2)}$

$T_{cond} \geq T_{brine} + \Delta T_{min}^{3}$

$CR_{max}F_{vapor} \geq F_{spv} \geq F_{vapor}$

$S_{brine} \geq S_{spec}$

Compressor Equations

Flow balance in compressor

$F_{spv} = F_{vapor}$

Compressor work

$W_{compr} = F_{spv}(H_{spv} - H_{vap})$

Isentropic temperature estimation

$T_{is} = (T_{vap} + 273)\left(\frac{P_{spv}}{P_{vapor}}\right)^{(\gamma-1)/\gamma}$

Temperature of superheated vapor

$T_{spv} = T_{brine} + \frac{1}{\eta}(T_{is} - T_{brine})$

Preheater Equations

Energy balance in preheater

$F_{vap}c_p^{cond}(T_{brine} - T_{freshwater}) = F_{in}c_p^{feed}(T_{in} - T_{feed})$

Area of preheater calculation

$A_{preheater} = \frac{F_{vap}c_p^{cond}(T_{brine} - T_{freshwater})}{U_{preheater}LMTD_{preheater}}$

LMTD preheater

$LMTD_{preheater} = (0.5\,\theta_1^{preheater}\,\theta_2^{preheater}(\theta_1^{preheater} + \theta_2^{preheater}))^{1/3}$

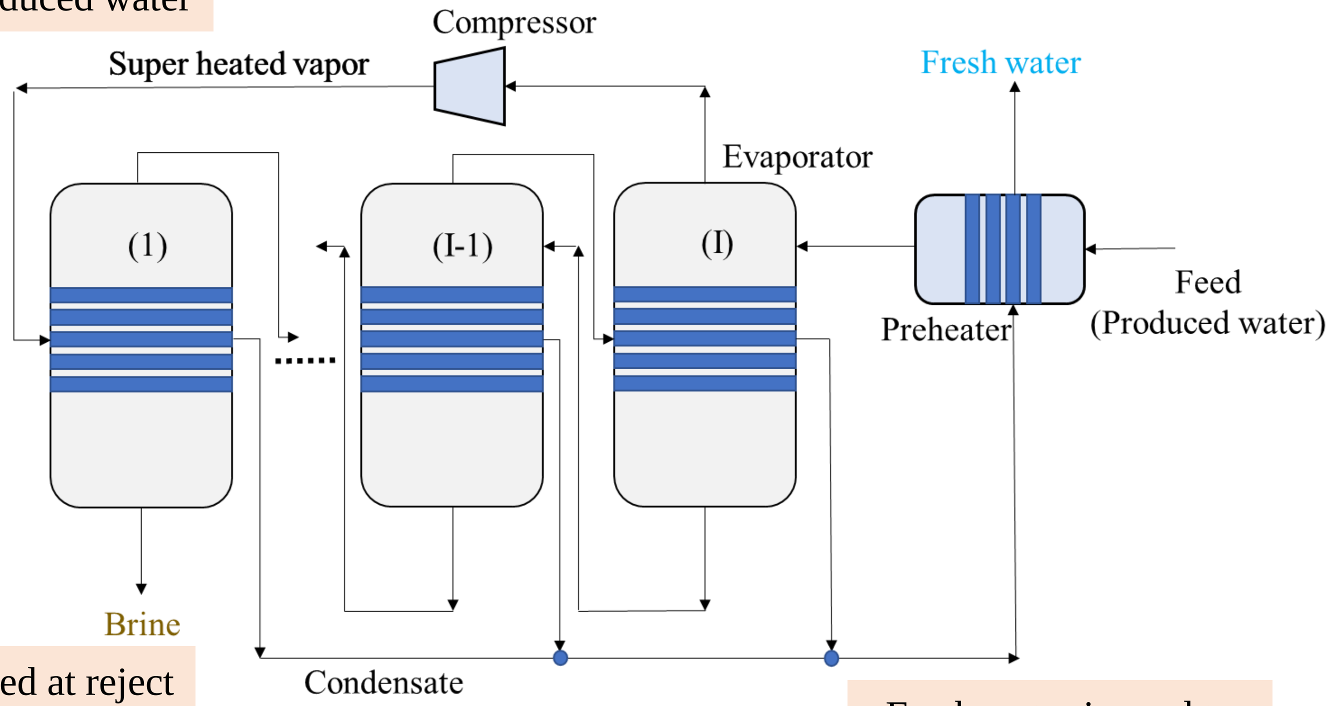
All enthalpies, heat transfer coefficients, BPE are calculated using empirical relations from Onishi 2017[1].
TAC is calculated using IDAES costing and compressor work

Desalination design and operation decisions can be integrated with network operation decisions

Mechanical Vapor Recompression

Vapor is compressed and used in the evaporator tubes for evaporating the shell side produced water

The only external energy supply to the system is to the compressor



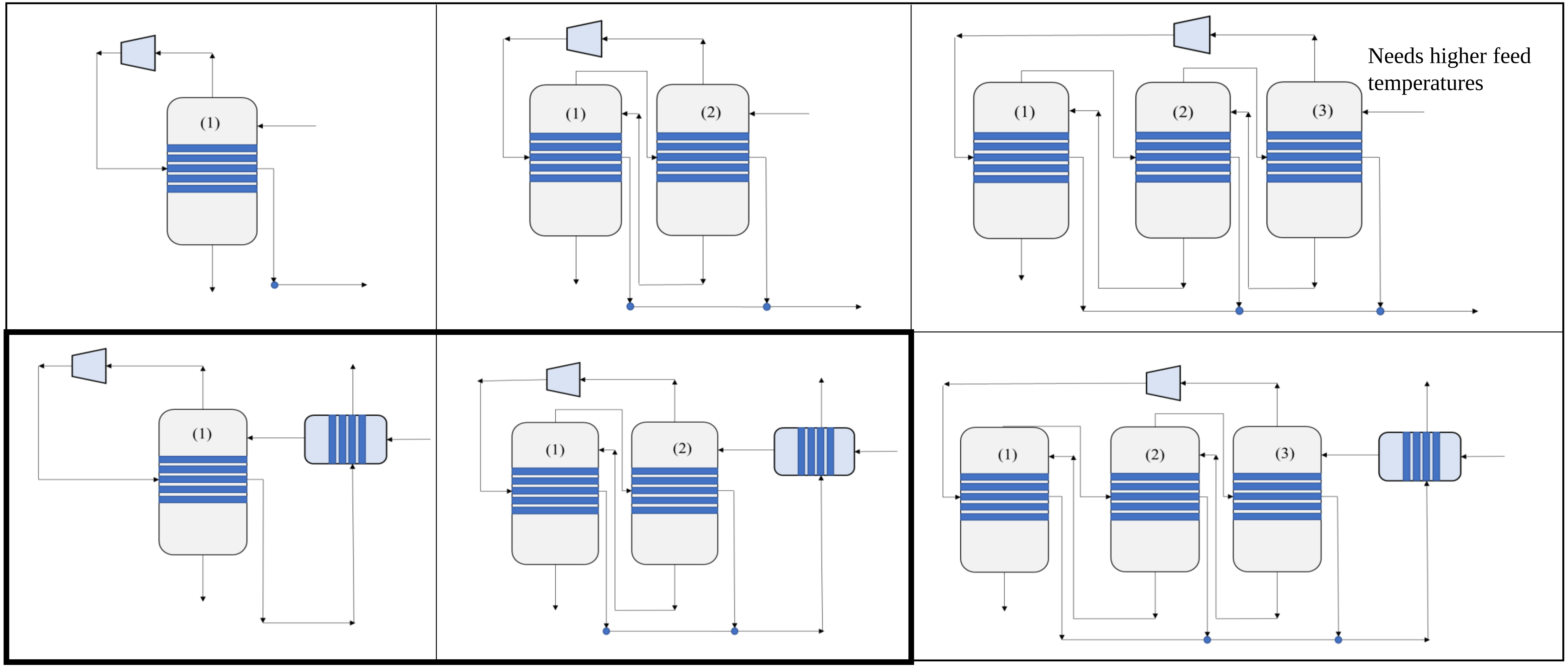
Operated at reject brine salinity

Fresh water is used to preheat the feed for further heat integration

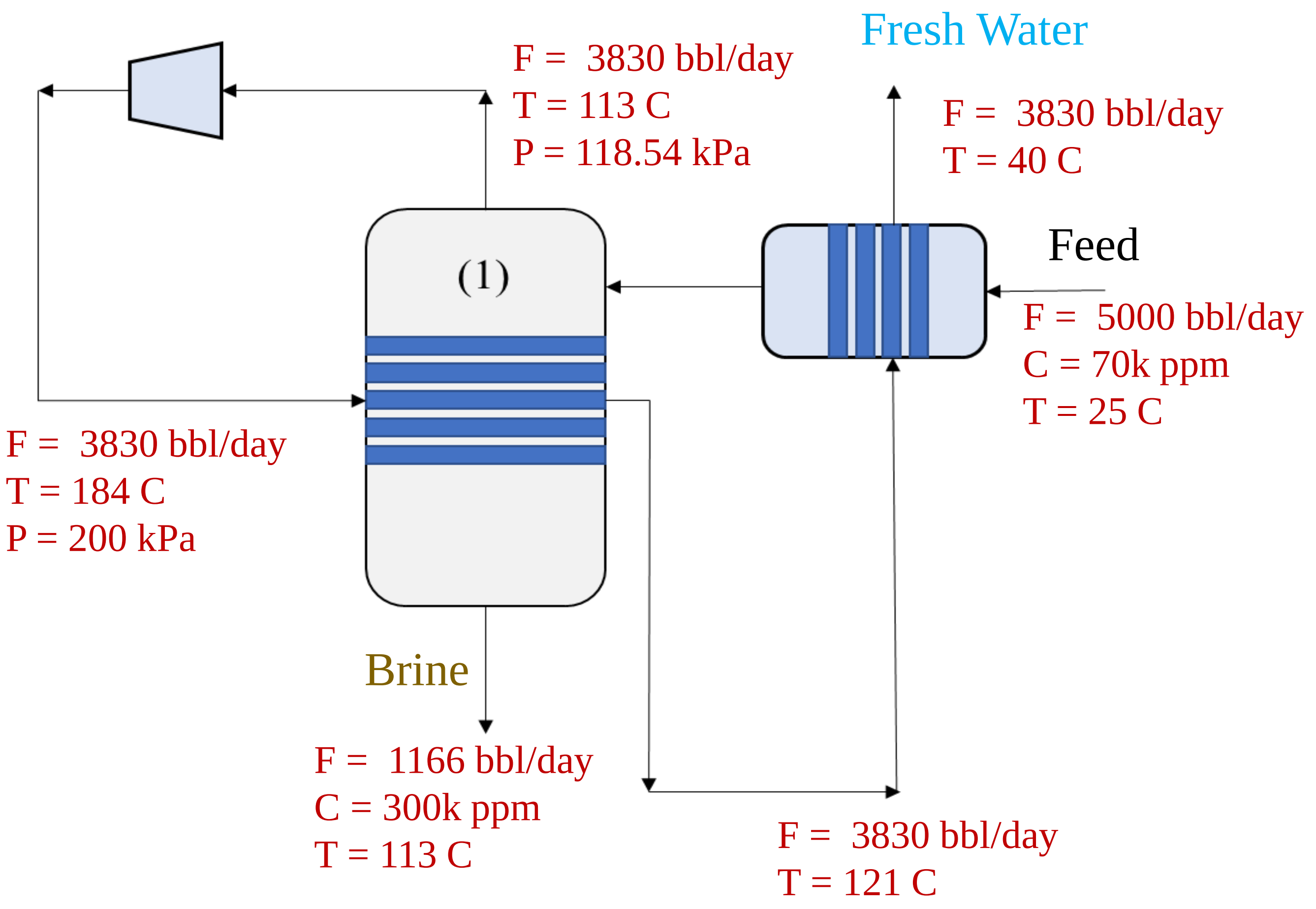
CAPEX:
1. Number of evaporation stages
2. Area of the evaporators
3. Area of the preheater
4. Compressor duty

OPEX:
1. Electricity consumed to run the compressor

Available MVR Superstructures



Optimal Single Stage MVR Design and Operation



Assumptions

Annual interest rate of 10 %

Amortization Period of 10 years

Optimal Desalination Plant Design

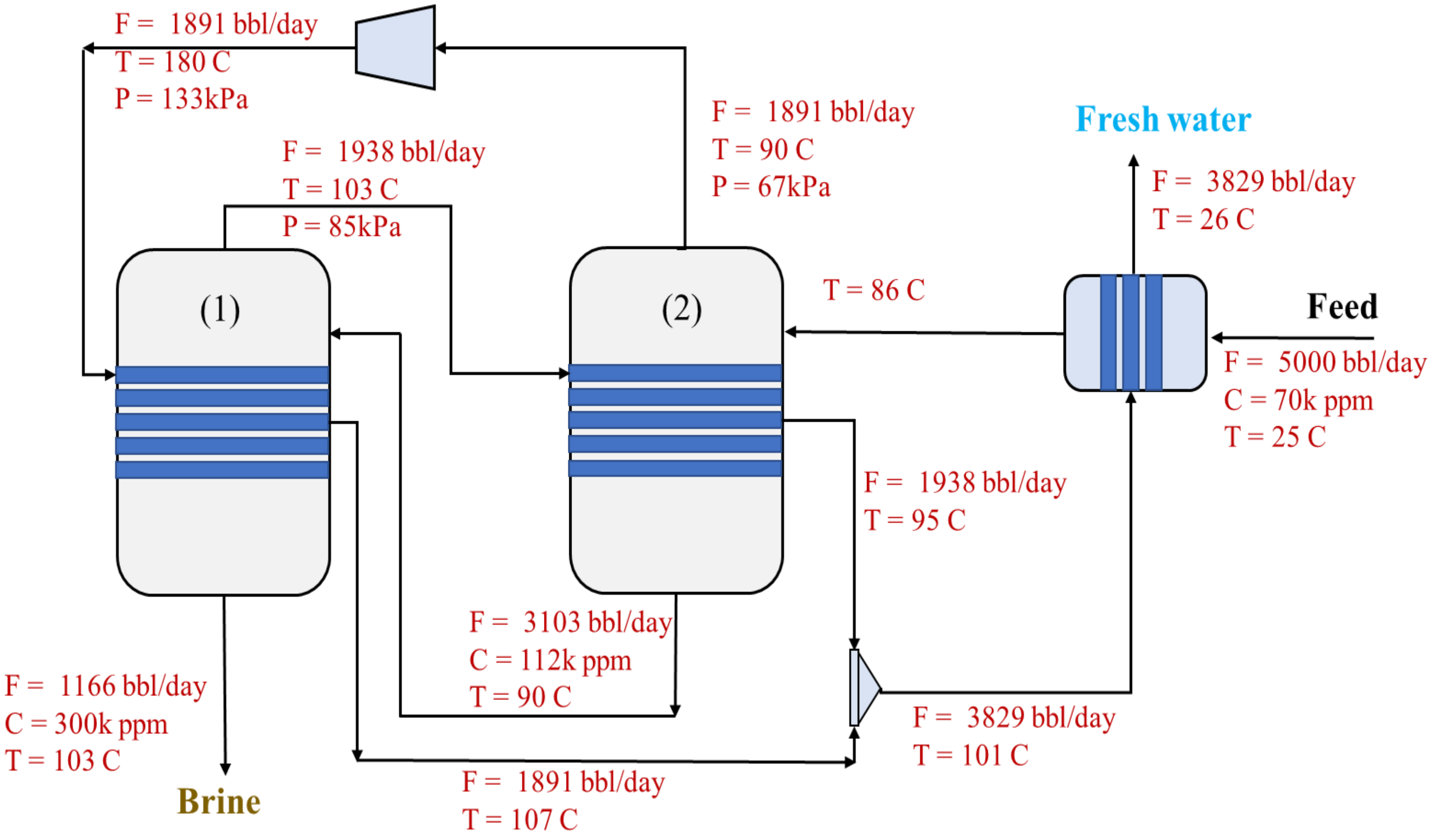
1. Compressor capacity: 1240 Hp
2. Evaporator area: 4004 ft^2
3. Preheater area: 90 ft^2

CAPEX: 165 kUSD/year

OPEX: 1296 kUSD/year

Desalination cost in $/bbl: 0.8 $/bbl

Optimal Two Stage MVR Design and Operation



<u>Assumptions</u>

Annual interest rate of 10 %

Amortization Period of 10 years

<u>Desalination Plant Design</u>

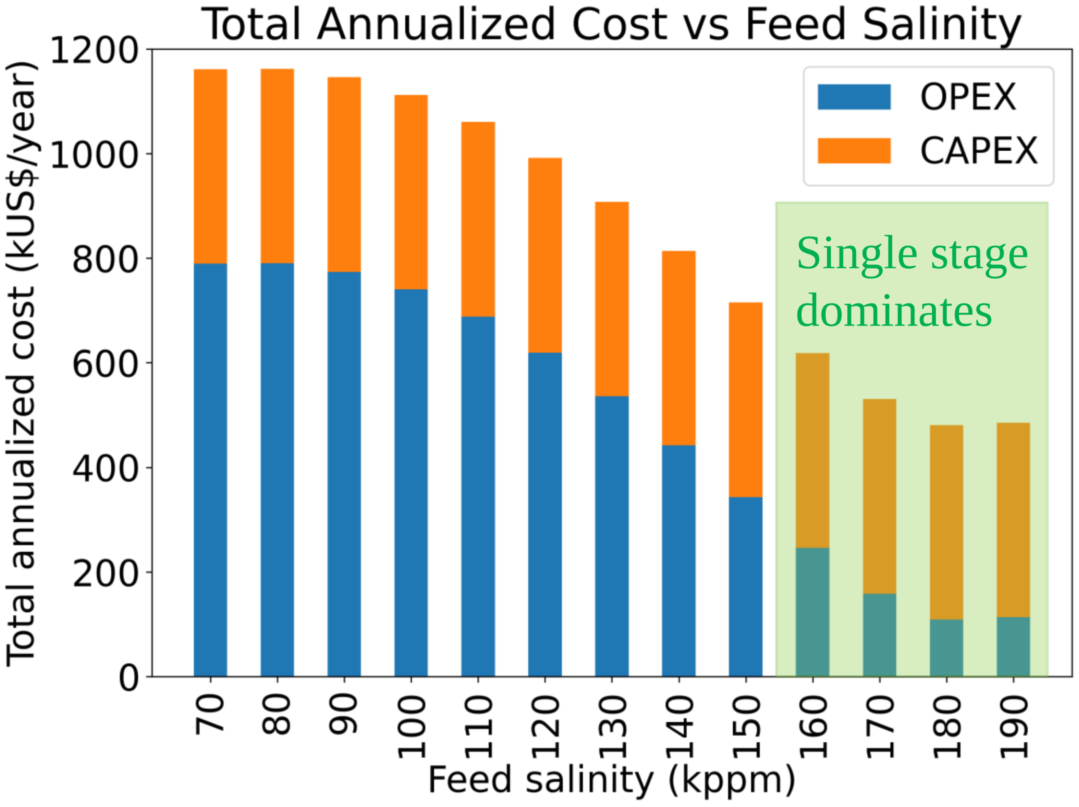
1. Compressor capacity: 770 Hp
2. Evaporator 1 area: 4004 ft^2
3. Evaporator 2 area: 4004 ft^2
4. Preheater area: 65 ft^2

CAPEX: 127kUSD/year

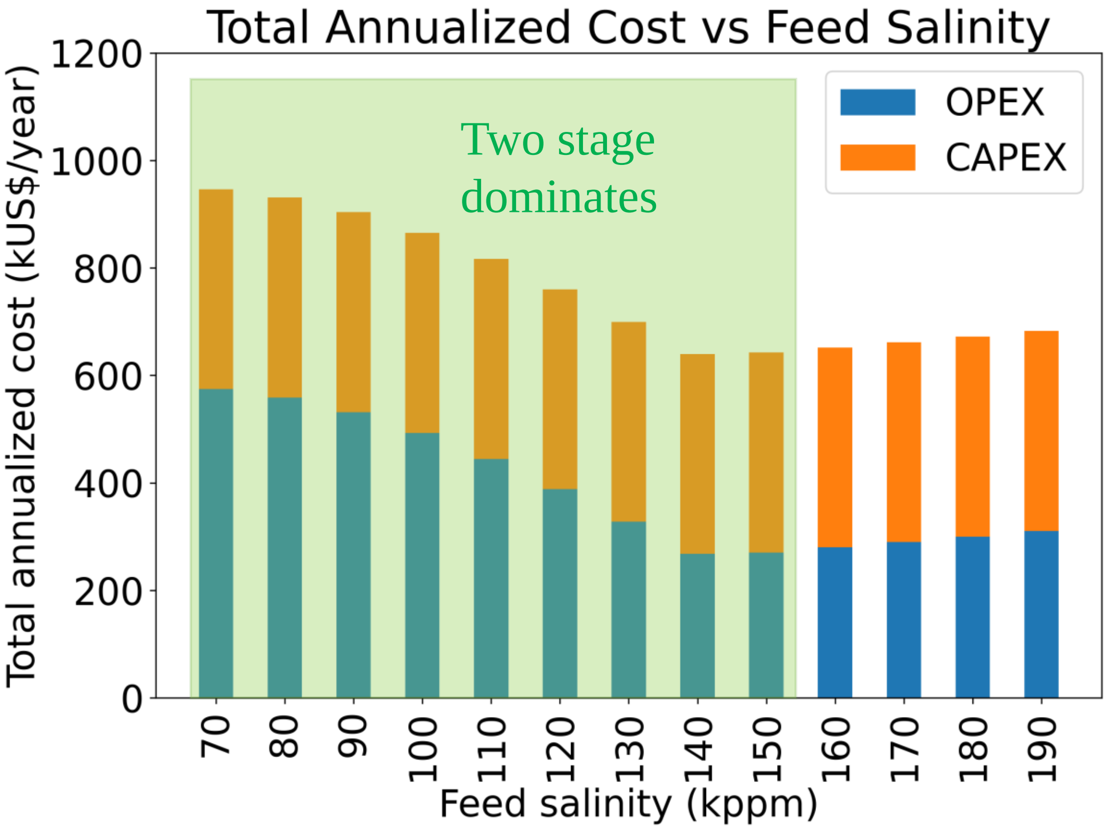
OPEX: 803kUSD/year

<u>Desalination cost in $/bbl</u>: 0.5 $/bbl

Sensitivity analysis for a lower bound on brine salinity



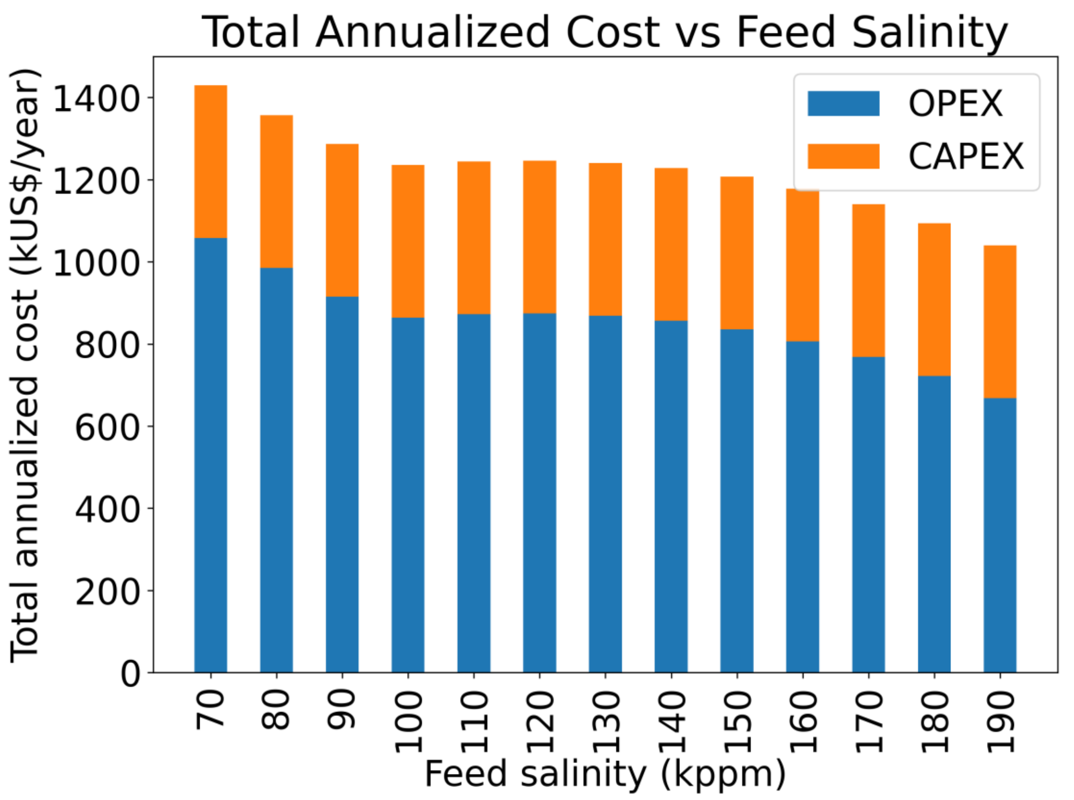
Single Stage Evaporation Optimal CAPEX and OPEX



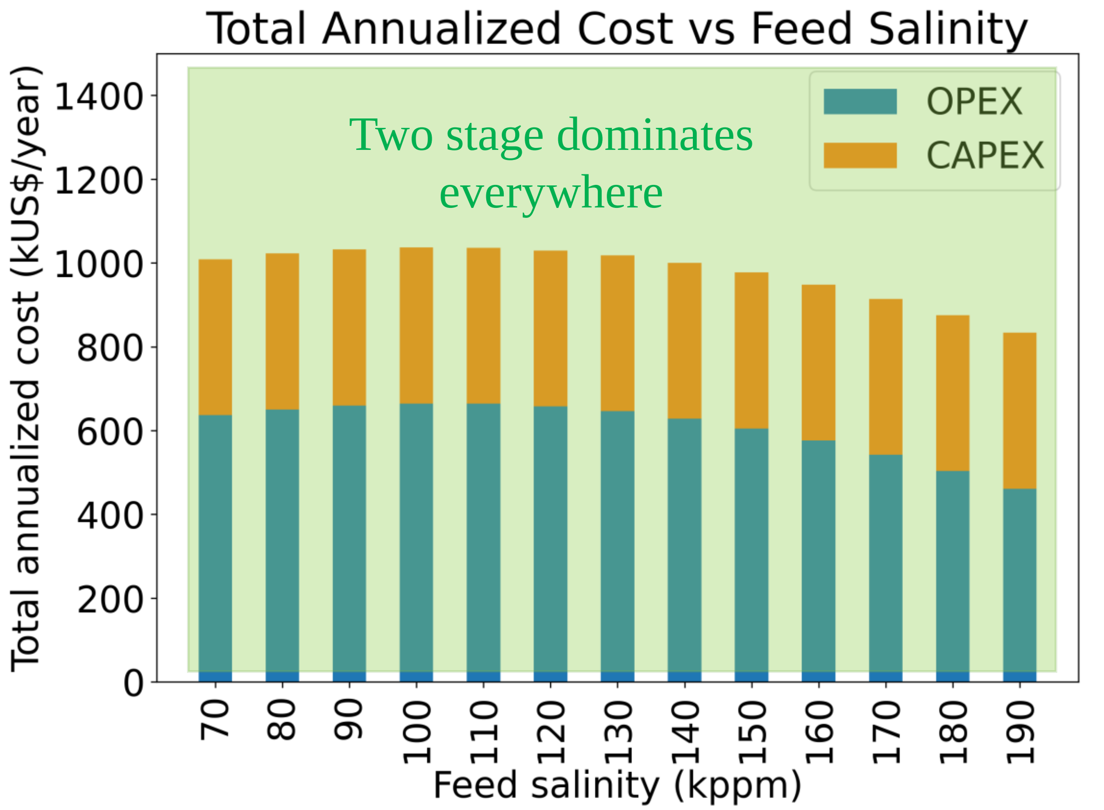
Two Stage Evaporation Optimal CAPEX and OPEX

Brine salinity ≥ 200k ppm

Sensitivity analysis for brine salinity set to saturation level



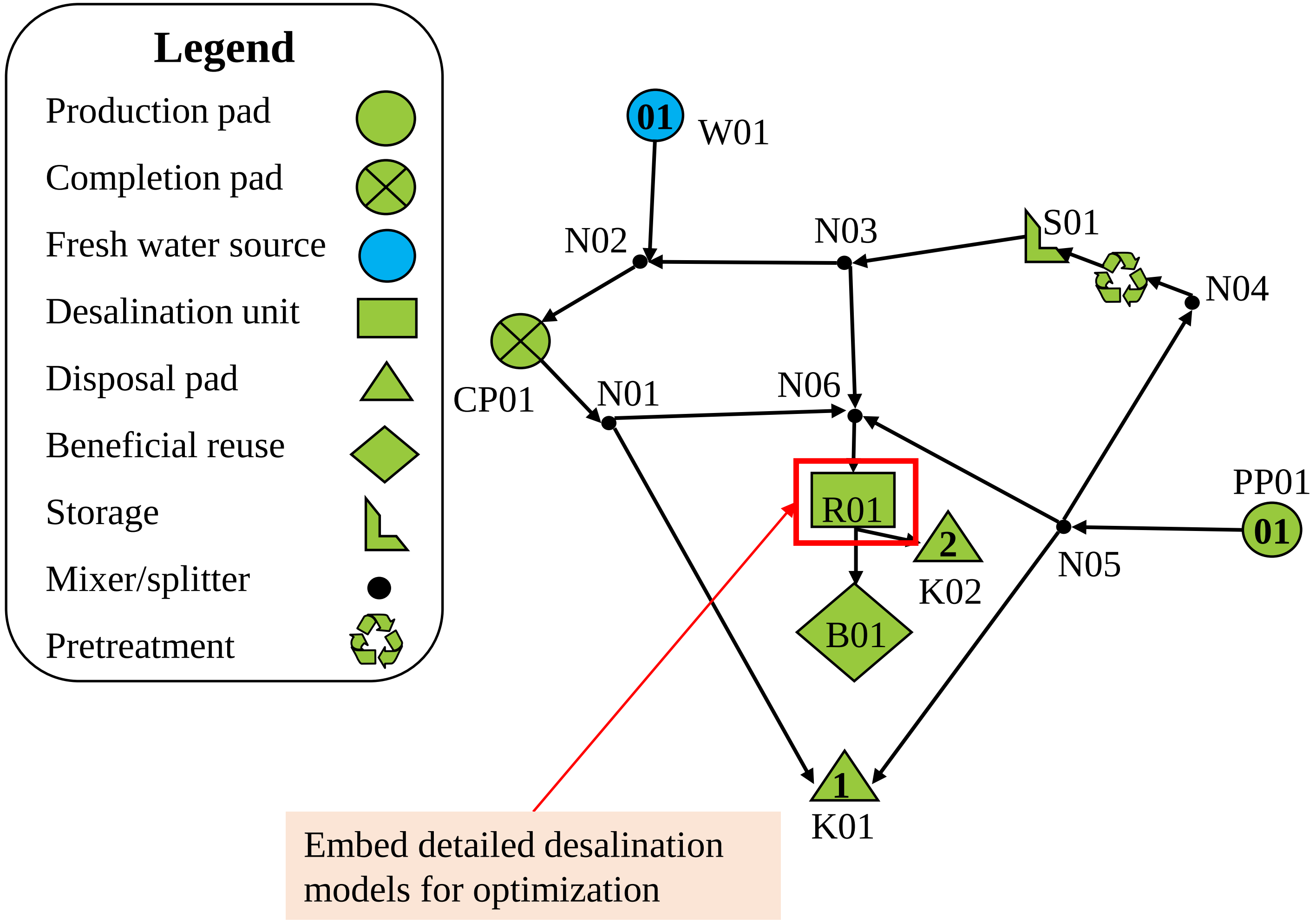
Single Stage Evaporation Optimal CAPEX and OPEX



Two Stage Evaporation Optimal CAPEX and OPEX

Brine salinity = 300k ppm (Zero liquid discharge condition)

Produced Water Network



Network Setup

1. The production pad produces water at different rates and salinities
2. The completions pad has different water requirements over the time horizon
3. Freshwater is limited
4. Storage and disposal have limited capacity
5. Desalinated water has value same as the cost of freshwater
6. Brine from the desalination has a salinity > 300k ppm (ZLD condition)

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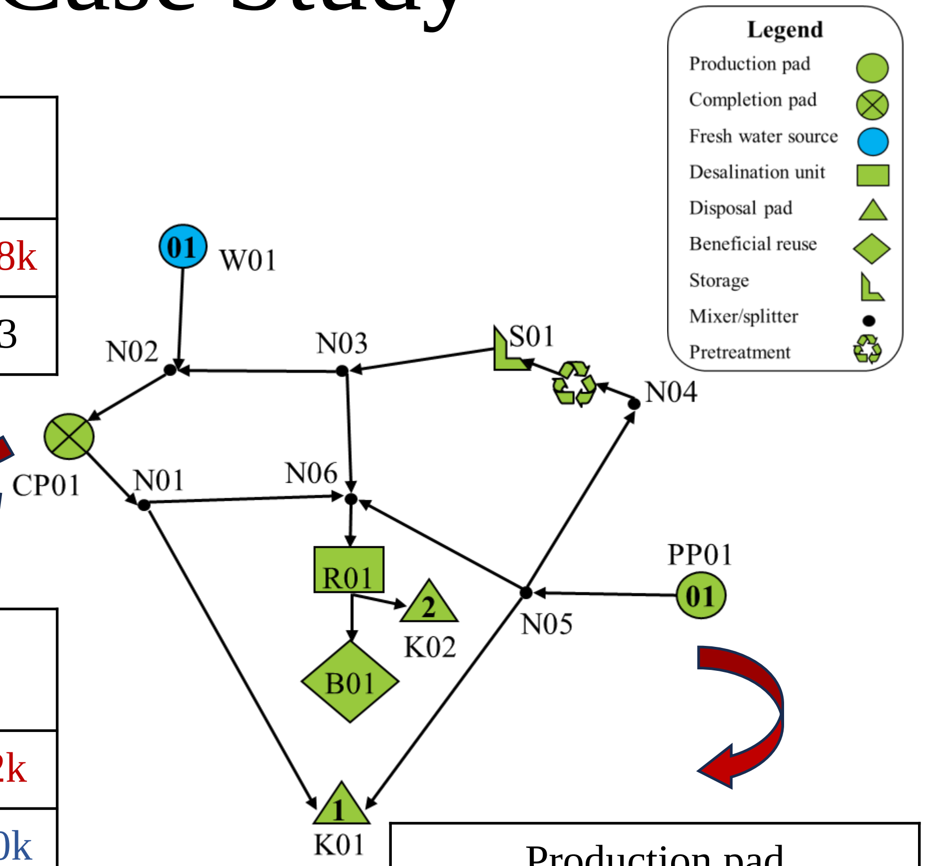
Network Case Study

Completions pad (consumption)	
Flowrate (bbl/day)	10.8k
Time period (days)	1-3

Completions pad (production)	
Flowrate (bbl/day)	9.2k
Salinity(ppm)	140k
Time period (days)	4-7



Production pad	
Flowrate (bbl/day)	16.3k
Salinity (ppm)	145k
Time period (days)	1-3

Note: Only for demonstration purposes. Doesn't represent actual flows and concentrations

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OPTIMAL CAPITAL AND OPERATING COST OF THE NETWORK FOR A WEEK

1. Piping cost = 13.2 kUSD
2. Fresh water cost = 0 kUSD
3. Disposal cost = 10 kUSD
4. Storage cost = 15.9 kUSD
5. Storage reward = 6.2 kUSD
6. Desalination CAPEX = 2.4 kUSD
7. Desalination OPEX = 12.3 kUSD
8. Desalination Reward = 4.7 kUSD

Total cost of the network: 44 kUSD

Total reward from the network: 11 kUSD

Note: These values depend upon the cost coefficients for storage, piping, disposal, fresh water and beneficial reuse. We don't account for the profits from oil.

Key Observations

1. 17% water is sent to disposal
2. 30% of total produced water is sent to desalination
3. No fresh water sourced

Desalination Plant Design

1. Compressor capacity: 743 Hp
2. Evaporator 1 area: 4004 ft^2
3. Evaporator 2 area: 4004 ft^2
4. Preheater area: 100 ft^2

Desalination Plant Cost

Capital cost breakdown:

1. Compressor: 0.27 kUSD/day
2. Evaporator: 0.06 kUSD/day
3. Preheater: 0.007 kUSD/day

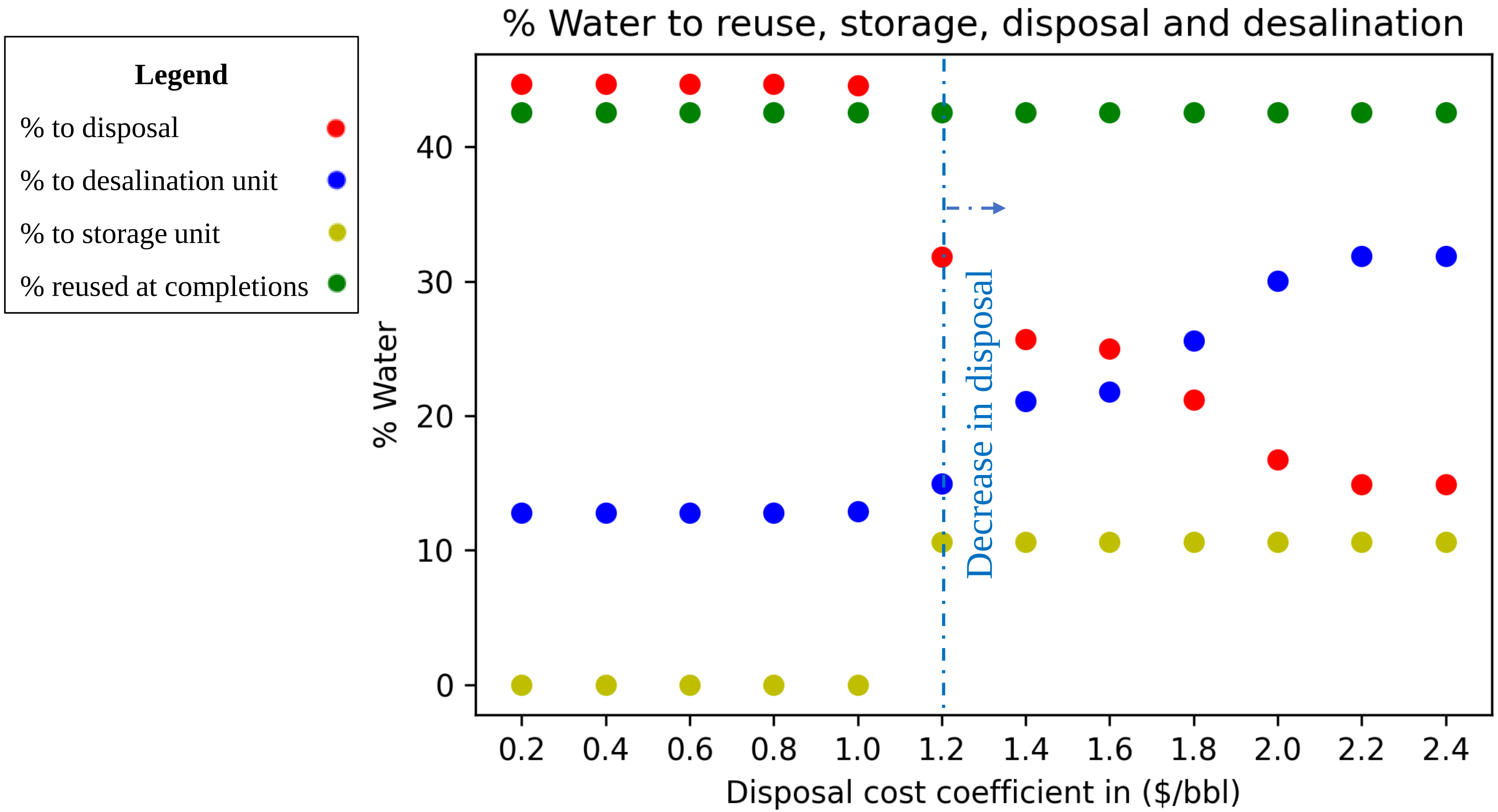
Operating cost breakdown:

Day 1 – Day 3: 0.94k USD/day

Day 4 – Day 7: 2.1k USD/day

Average desalination cost in $/bbl: 0.5 $/bbl

Disposal costs increase due to restrictions on disposal



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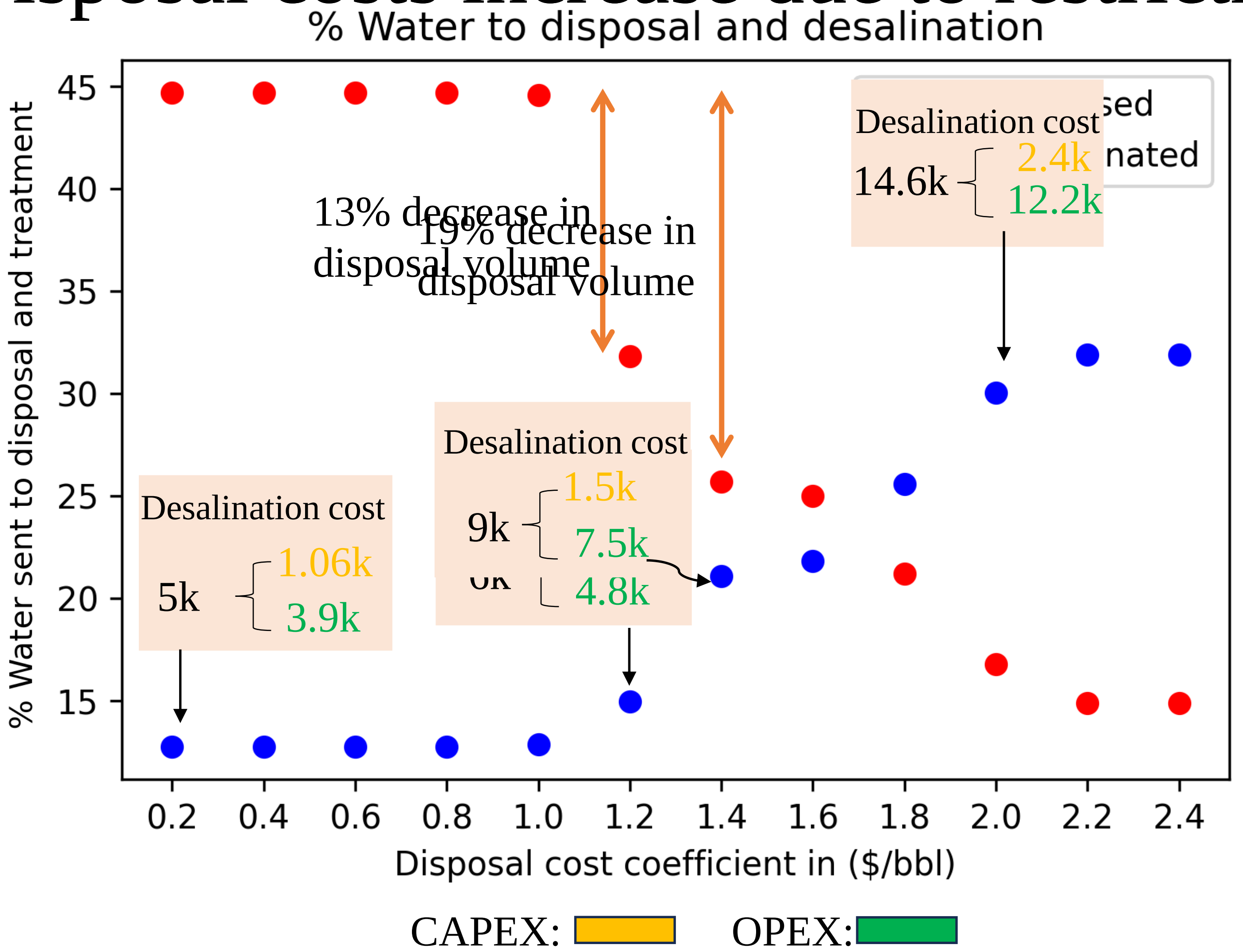

Maximum desalination capacity

Key Conclusions

1. When disposal is cheap, smaller desalination unit is built
2. When disposal is expensive, preference is to desalinate water

Conclusions

1. Mechanical vapor recompression is identified as a potential desalination technology for produced water
2. Design of desalination units depends upon the volume and salinity of produced water and outlet brine specifications
3. Desalination design and operation can be integrated into network operation
4. When disposal costs are high, it is beneficial to desalinate more water than dispose

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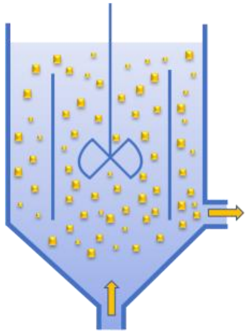
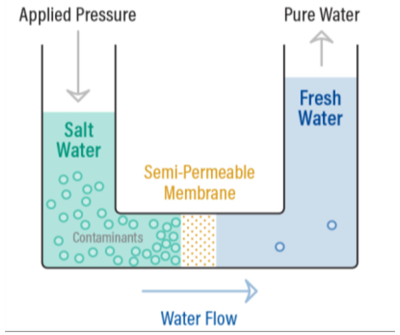
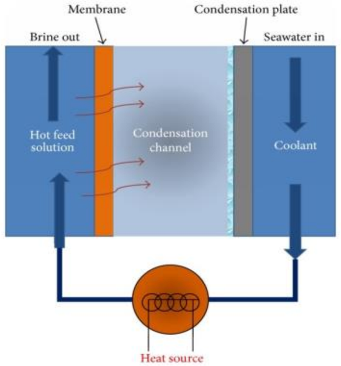
Future Work



Crystallization

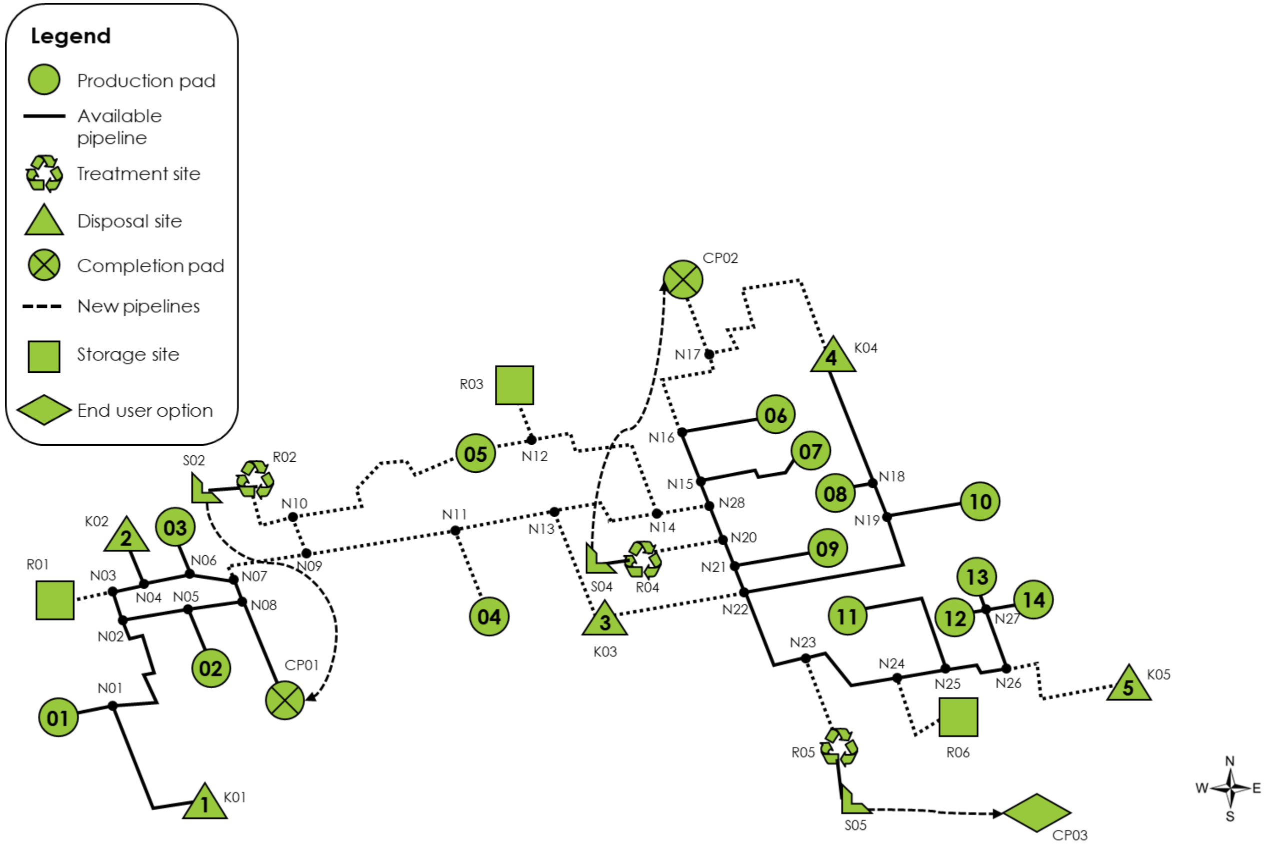


Reverse Osmosis



Membrane distillation

Build mathematical models for other desalination strategies



Integrate desalination into larger case studies and a planning horizon of one year

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