Model-Based Extracted Water Desalination System for Carbon Sequestration

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Imagination at work.

Crosscutting Research & Rare Earth Elements Portfolios Review
March 23, 2017

GE Global Research Team

Name	Background	Role
Liz Dees	PhD, Chemical Engineering	co-PI, Techno-economic modeling
Ryan Adams	PhD, Chemical Engineering	Piloting, techno-economic models
Rachel Gettings	MS, Marine Biology	Piloting, techno-economic models
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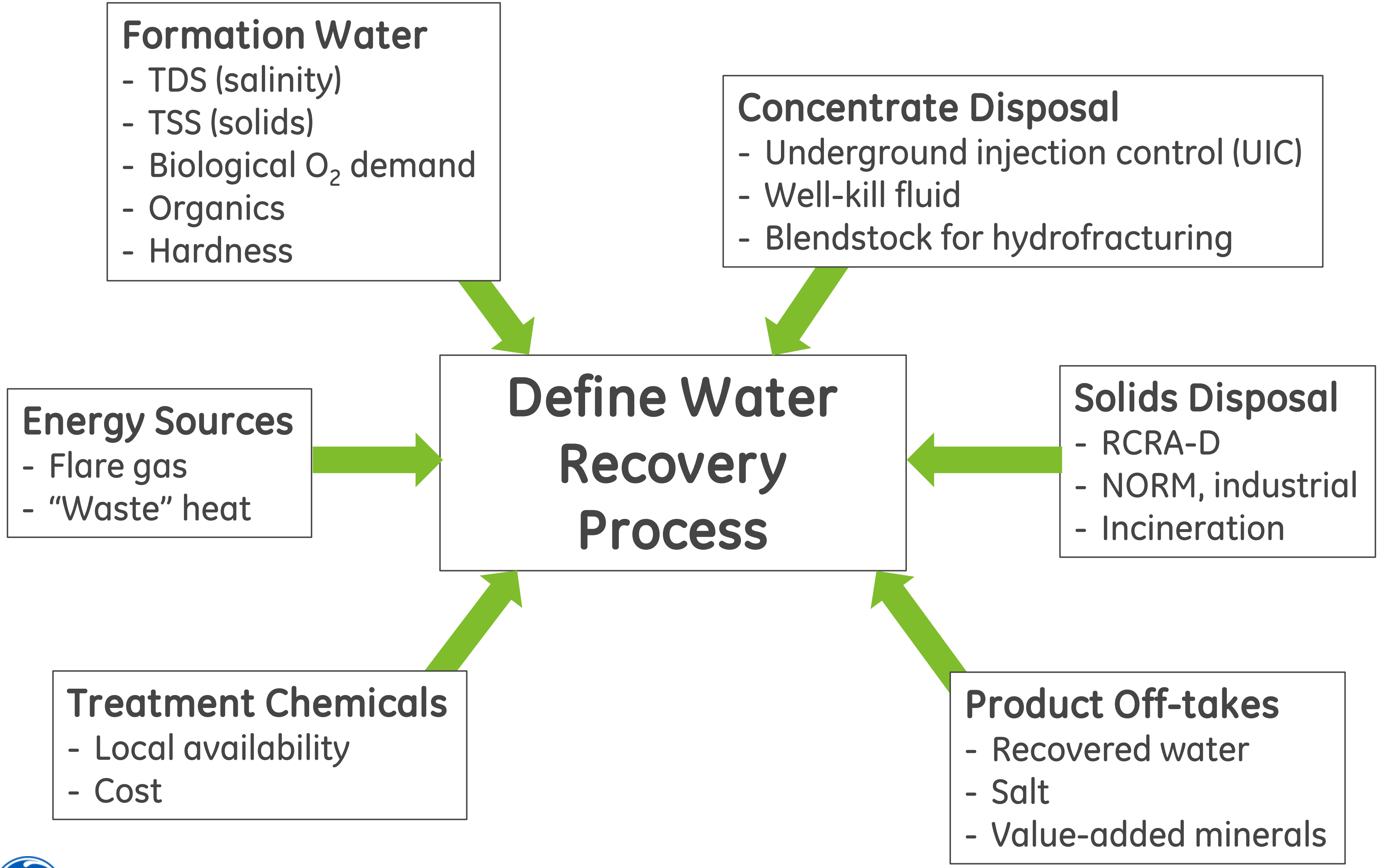
Al Stella	PhD, Chemical Engineering	techno-economic models
Bill Alberts	BS, Process Engineering	Piloting/Testing

The Pennsylvania State University (subcontractor)

Name	Background	Role
Li Li	PhD, Environmental Engineering	Task 2: Site identification
Manish Kumar	PhD, Environmental Engineering	Task 3: High pressure RO

Objective: Defining Water Recovery Process



Define Water Recovery Process

Formation Water
- TDS (salinity)
- TSS (solids)
- Biological O_2 demand
- Organics
- Hardness

Concentrate Disposal
- Underground injection control (UIC)
- Well-kill fluid
- Blendstock for hydrofracturing

Energy Sources
- Flare gas
- “Waste” heat

Solids Disposal
- RCRA-D
- NORM, industrial
- Incineration

Treatment Chemicals
- Local availability
- Cost

Product Off-takes
- Recovered water
- Salt
- Value-added minerals

Strategy for Defining Water Recovery Process

1. Define Base Case

- Conventional desalination technology
- Assess required pretreatment needs
- Key question: generate a solid NaCl product?

2. Compare Base Case & Alternative Desalination Technologies

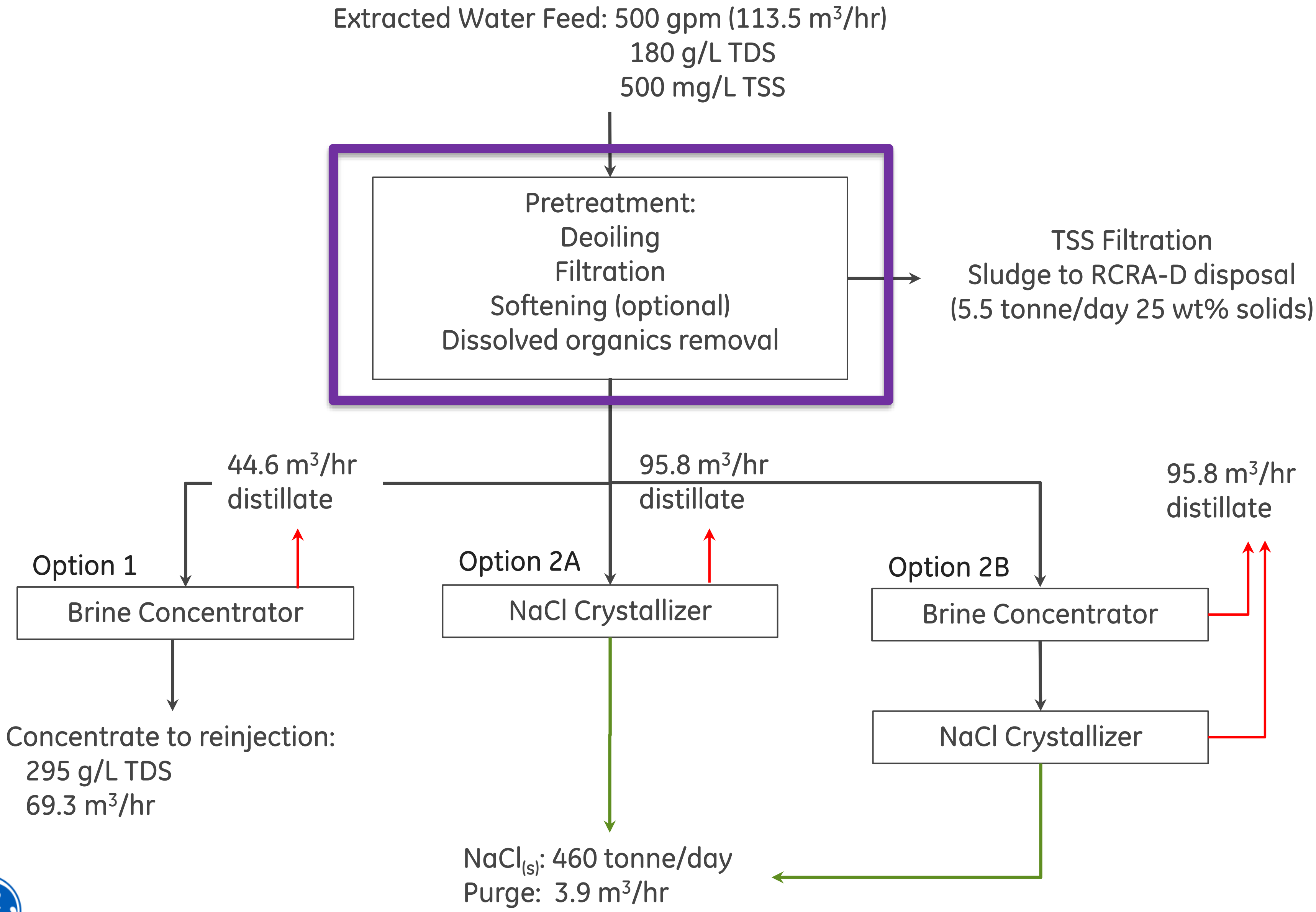
- Softening required?
  - Aspen Plus and Excel models
  - Cost of softening chemicals
- Techno-economic modeling of desalination processes
  - Aspen Plus and Excel models
  - Cost results (normalized by base case cost)

3. Validation of Pilot Readiness

- Bench & pre-pilot scale experiments
- Model refinement

1. Define Base Case

Pretreatment



Extracted Water Feed: 500 gpm (113.5 m^3/hr)
180 g/L TDS
500 mg/L TSS

Pretreatment:
Deoiling
Filtration
Softening (optional)
Dissolved organics removal

TSS Filtration
Sludge to RCRA-D disposal
(5.5 tonne/day 25 wt% solids)

Option 1

Brine Concentrator

44.6 m^3/hr
distillate

Concentrate to reinjection:
295 g/L TDS
69.3 m^3/hr

Option 2A

NaCl Crystallizer

95.8 m^3/hr
distillate

Option 2B

Brine Concentrator

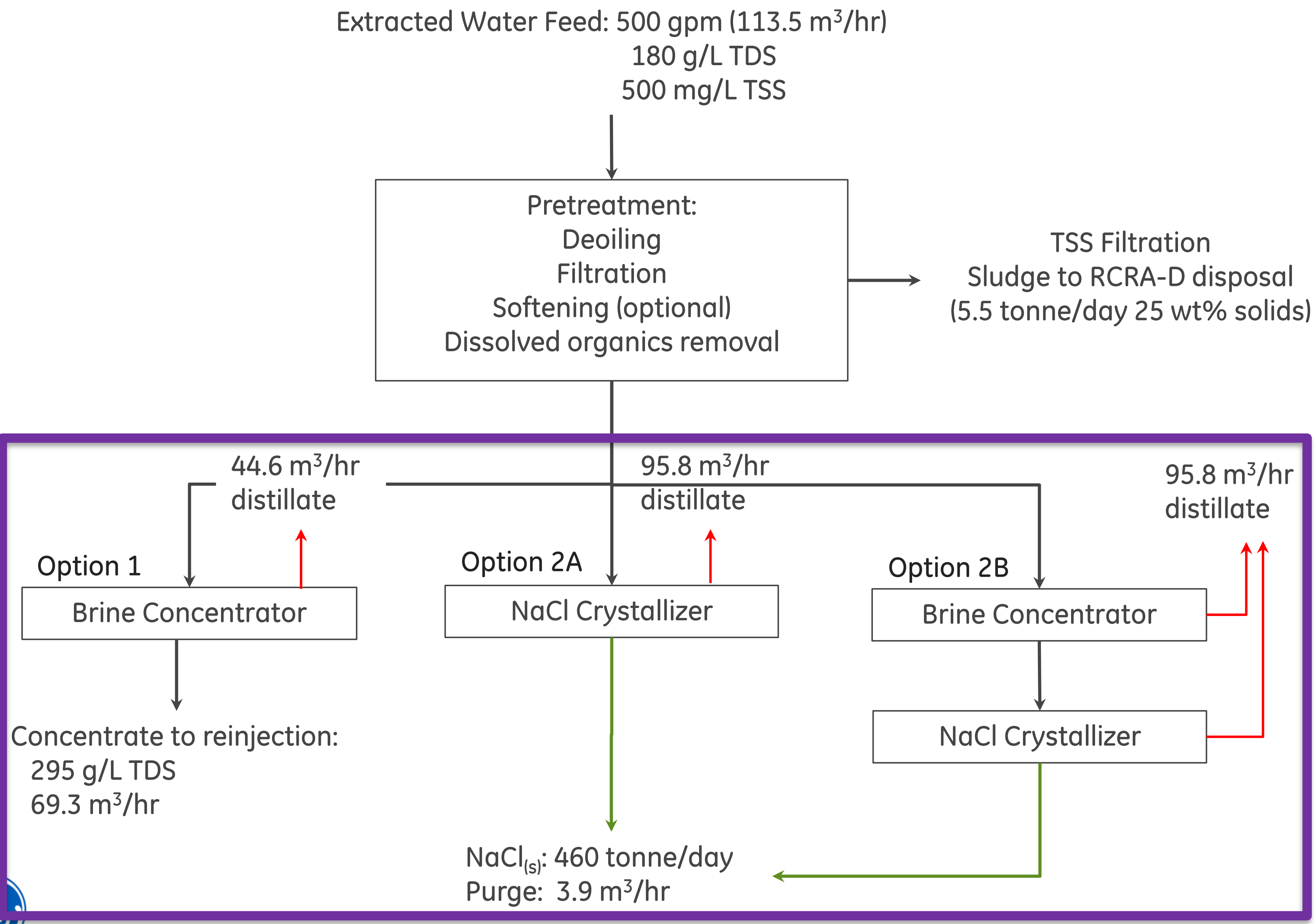
NaCl Crystallizer

95.8 m^3/hr
distillate

$NaCl_{(s)}$: 460 tonne/day
Purge: 3.9 m^3/hr

1. Define Base Case

Conventional Desalination



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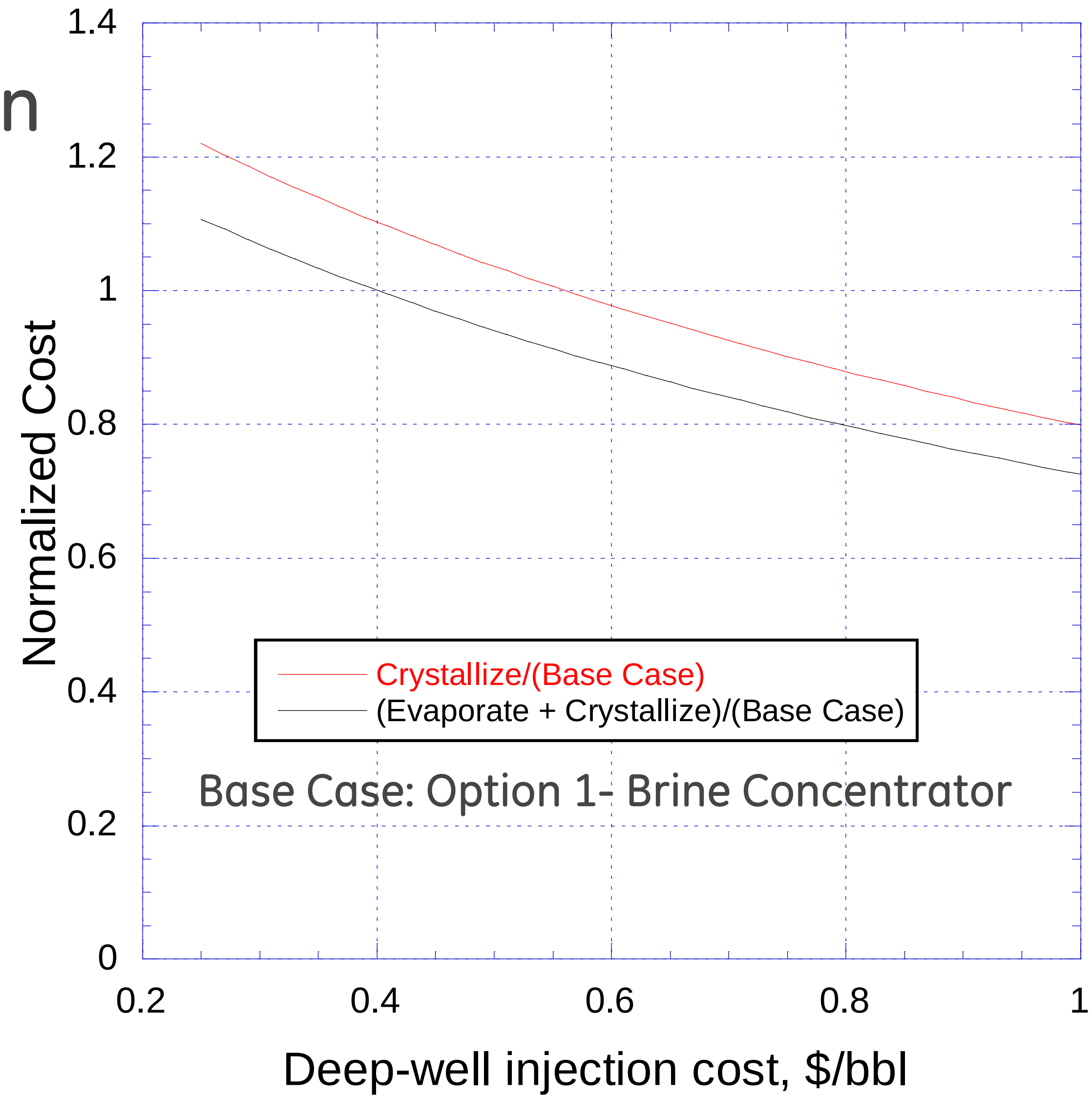
$NaCl_{(s)}$: 460 tonne/day
Purge: 3.9 m^3/hr

Base Case Desalination Options Comparison

Cost model details

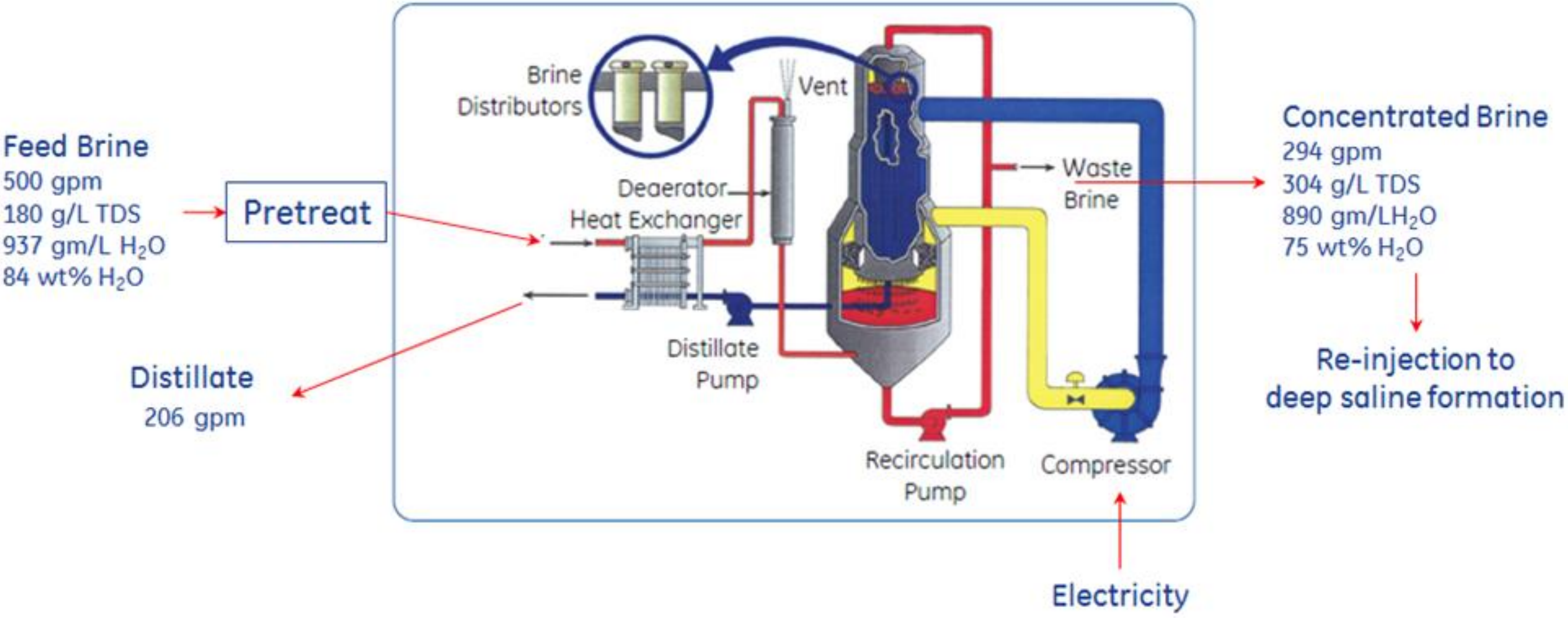
- Feed: 113.5 m^3/hr, 180 gm/L TDS, $0.40/bbl reinjection cost
- Installed CAPEX
- Electricity for compressor
- Concentrate or purge disposal
- Pretreatment ($0.25/bbl), no softening
- No credit for distilled water, salt
- Out-of-scope: effect of parasitic load on process economics



Base Case: Option 1- Brine Concentrator

Option 1 lowest cost for UIC < $0.40/bbl…selected for base case

Base Brine Concentrator: Falling Film Mechanical Vapor Recompression (FF-MVR)



Feed Brine
500 gpm
180 g/L TDS
937 gm/L H_2O
84 wt% H_2O

Pretreat

Distillate
206 gpm

Concentrated Brine
294 gpm
304 g/L TDS
890 gm/LH_2O
75 wt% H_2O

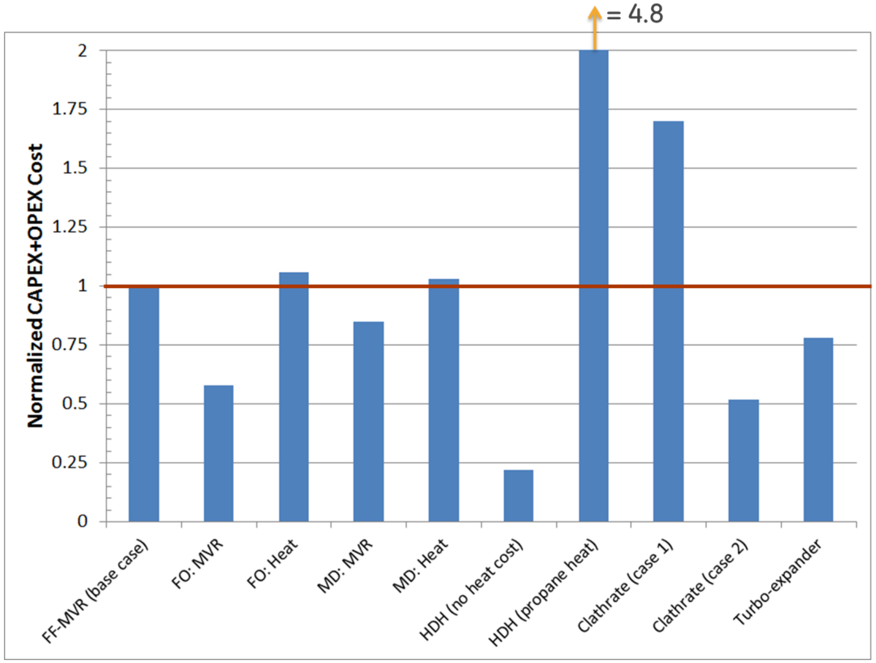
Re-injection to deep saline formation

Electricity

Alternate Brine Concentration Technologies

Suitable for high TDS (180 g/L) extracted water:

1. Forward Osmosis (FO)
2. Membrane Distillation (MD)
3. Humidification-Dehumidification (HDH)
4. Clathrate Chemical Complexation
5. Turbo-Expander-based Freezing
6. High Pressure Reverse Osmosis



Softening Chemistry

$$MgCl_2 + 2NaOH \rightarrow Mg(OH)_{2(s)} + 2NaCl$$

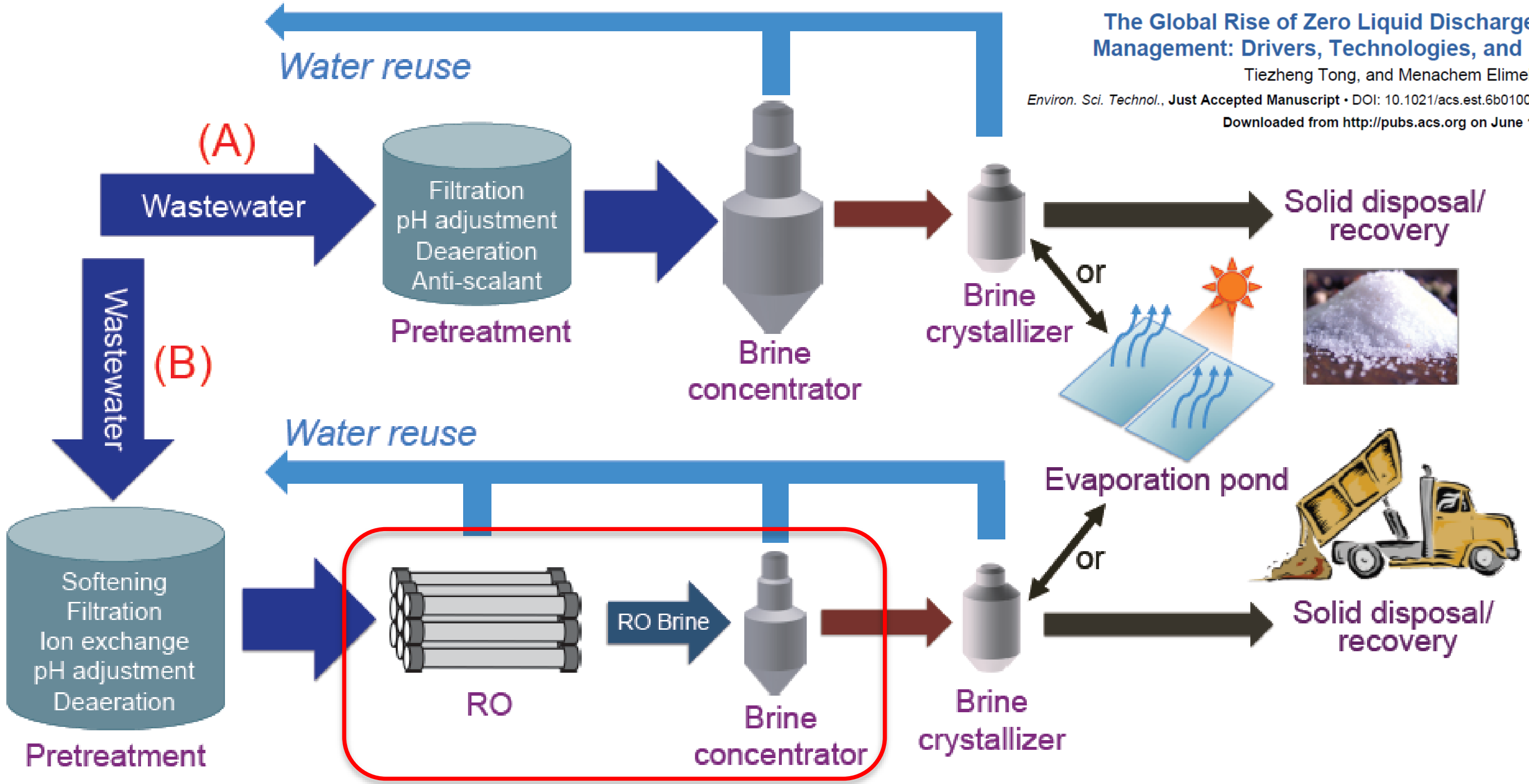
$$CaCl_2 + Na_2CO_3 \rightarrow CaCO_{3(s)} + 2NaCl$$

$$SrCl_2 + Na_2CO_3 \rightarrow SrCO_{3(s)} + 2NaCl$$

Feed Mg^{++}	lb-mole/hr	14.704
Feed Ca^{++} + Sr^{++}	lb-mole/hr	63.838
Na_2SO_4 added as 100% (optional)	lb/hr	4.85
NaOH added (100%)	lb/hr	1175.0
Na_2CO_3 added (100%)	lb/hr	7203.0
HCl for neutralization (100%)	lb/hr	105.4
Sludge generated (25 wt% solids)	short ton/hr	14.82
Na_2SO_4 cost	\$/hr	\$0.325
NaOH cost	\$/hr	\$325.1
Na_2CO_3 cost	\$/hr	\$1149
HCl cost	\$/hr	\$25.10
Sludge disposal	\$/hr	\$741.1
Total softening cost	\$/hr	\$2240
Net distillate	m^3/hr	44.58
Softening cost	**\$/m^3 net distillate**	**\$50.25**

High cost of softening hard waters limits alternate desalination options

RO Preconcentration for Brine Concentrator Size & Energy Reduction



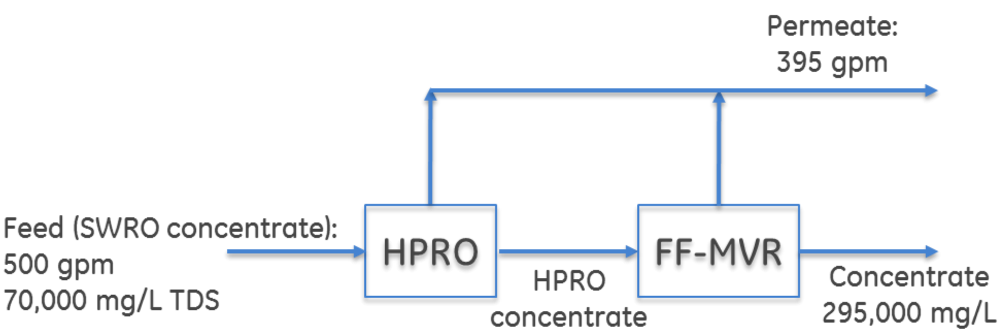
The Global Rise of Zero Liquid Discharge for Wastewater Management: Drivers, Technologies, and Future Directions
Tiezheng Tong, and Menachem Elimelech
Environ. Sci. Technol., **Just Accepted Manuscript** • DOI: 10.1021/acs.est.6b01000 • Publication Date (Web): 08 Jun 2016
Downloaded from http://pubs.acs.org on June 13, 2016

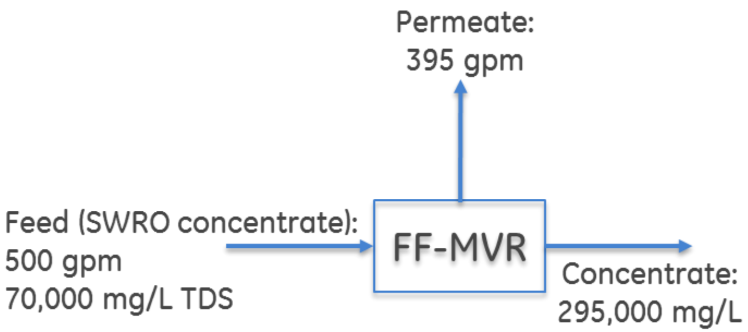
Technical risks of RO at high TDS:

Challenge	Need
Scaling	Fouling-resistant membrane & module; adequate pretreatment
Compaction	Membrane & module performance stable at high feed pressure

Technoeconomics: Hybrid HPRO + FF-MVR vs. FF-MVR

SWRO concentrate case: hybrid HPRO + FF-MVR system





HPRO concentrate TDS (mg/L)	Normalized cost (HPRO+FF-MVR/FF-MVR)
130,000	0.53
175,000	0.47
245,000	0.49

Hybrid HPRO + FF-MVR system estimated to be ~1/2 the cost of FF-MVR

Technical risks: membrane & element performance, compaction, water chemistry (scaling)

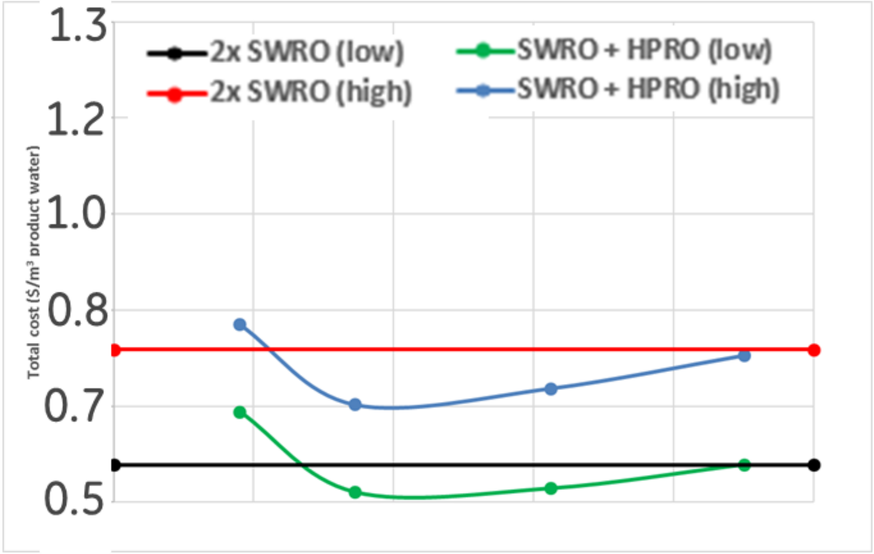
3. Pilot Readiness
Model refinement

SWRO + HPRO Hybrid Technoeconomics Summary

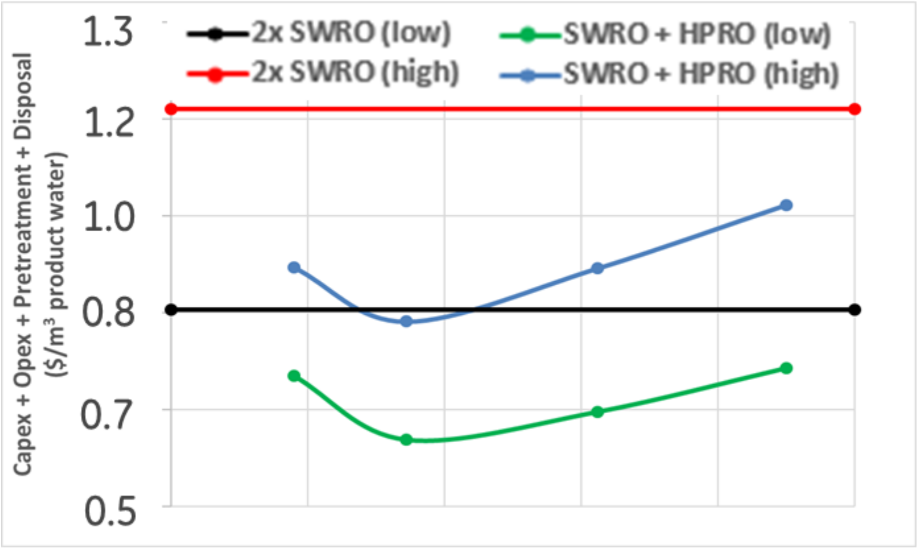

Seawater RO

SWRO → HPRO vs. SWRO

2x concentrate disposal cost →



Increasing system size
Increasing concentrate volume
Decreasing pressure requirement

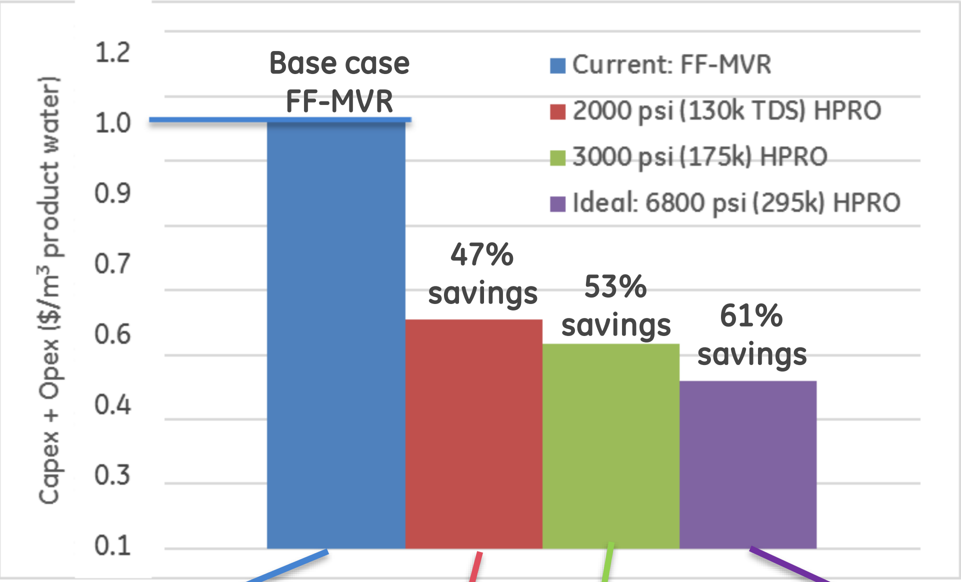


Increasing system size
Increasing concentrate volume
Decreasing pressure requirement

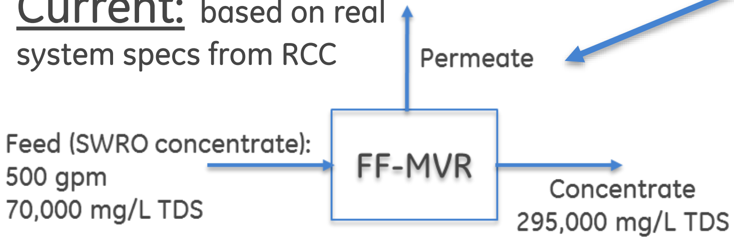
SWRO + HPRO hybrid reduces system cost in many cases
(dependent on HPRO material, pretreatment & concentrate disposal costs)

3. Pilot Readiness Model refinement

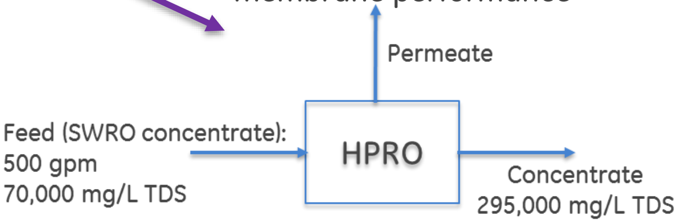
Current vs. Ideal HPRO techno-economics



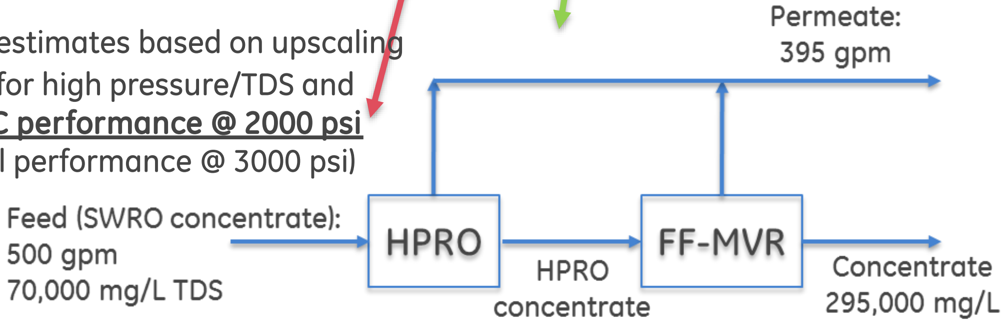
Current: based on real system specs from RCC



Ideal: estimate based on upscaling SeaPRO-84 for high pressure/TDS and aspirational membrane performance



Hybrid: estimates based on upscaling SeaPRO-84 for high pressure/TDS and **current GRC performance @ 2000 psi** (aspirational performance @ 3000 psi)



Produced Water Treatment Facility

On-site pilot-scale proving grounds for separation materials & unit operations R&D

Microfiltration Unit: 2 GPM permeate
with < 10 NTU, auto-backwash

Ultrafiltration Unit: ≤ 5 GPM permeate
for removing fines, oily colloids

Steam Regenerable Sorbent (SRS) Unit: ≤ 2 kg resin, ≥ 0.5 LPM, “field” flow profile, ≤ 235 psig steam (≤ 200 °C)

Feed: Tank + Controls

Resin Column

Backwash/Steam Controls

Steam Generator

- Comprehensive analytics on-site & off-site: LC-OCND, TDS, TSS, TOC, cond., BTEX/GRO/DRO

GRC High Pressure Test Bench

High Pressure Bench w/ 1812 Module Housing

1812 module housing

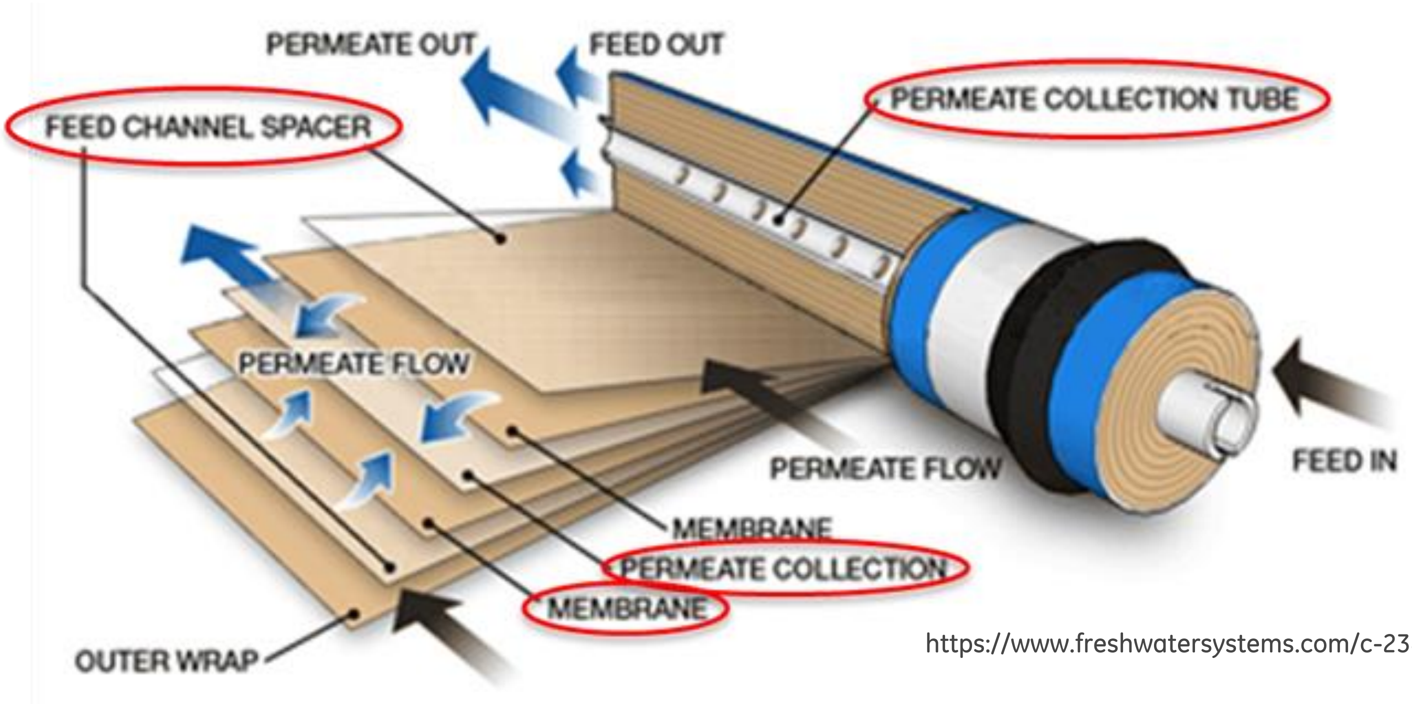
High pressure pump

High Pressure Bench w/ Coupon Cell

Coupon cell

High pressure bench can test an 1812 module or flat sheet membrane at pressures up to 4000-5000 psig

Components Critical for High Pressure RO



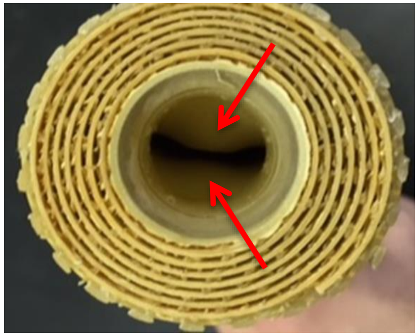
https://www.freshwatersystems.com/c-238-ro-membranes.aspx

- Identify components responsible for performance loss at high TDS/pressure
- Replace components with suitable alternatives to maximize TDS/pressure operation range of spiral-wound RO module

GRC Results

Existing

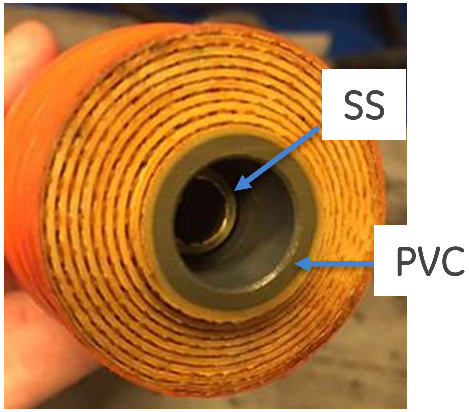
Permeate tube crushed at 2900 psi



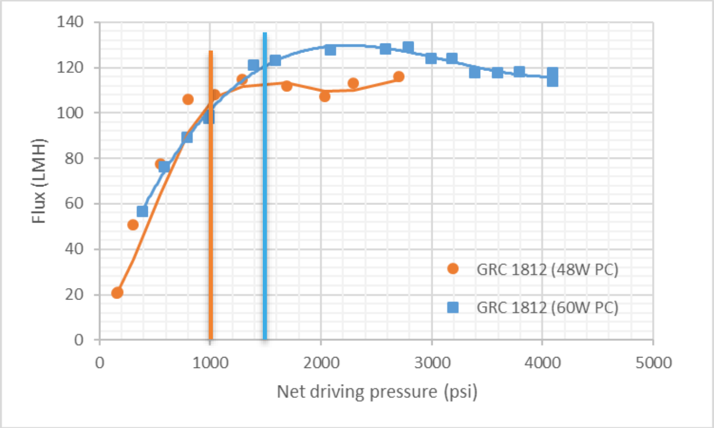
Cracks in membrane and permeate tube

Eliminate Gross Failure

Re-enforced core tube: intact to 4800 psi (did not fail)



Minimize Compaction

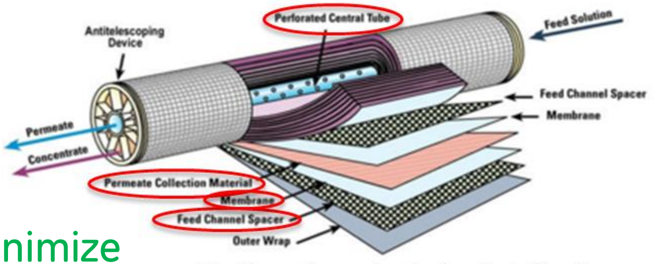


Compaction onset (NDP):
PC1 : 1000 psi
PC2: 1500 psi

Maximum pressure achieved: 4800 psi (no failure)
Compaction onset NDP increased from 1000 to 1500 psi

Module Improvements

Existing → Eliminate Gross Failure → Minimize Compaction



http://www.lixus.net.cn/en/products/Membrane.aspx

Component	Standard 1812	1st HPRO elements	2nd HPRO elements	Next steps
Membrane	AG	AG	AG	AD
Feed spacer	34 mil	30 mil	30 mil	30, 45 or 65 mil
Permeate carrier	Standard	PC1(a)	PC1(b)	Alternate materials
Core tube	Standard	Reinforced	Reinforced	-
Failure pressure (psi)	2900 psi – crushed core tube	n/a (up to 3200 psi)	n/a (up to 4800 psi)	-
Compaction NDP (psi)	800	1000	1500	Membrane Development

Reinforced core tube prevents gross failure
Next steps: identify/develop materials to minimize membrane compaction

Acknowledgments

U.S. DEPARTMENT OF ENERGY

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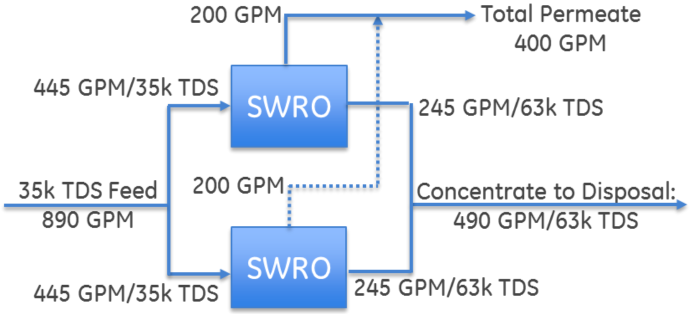
Water & Process Technologies

Disclaimer

Acknowledgment: "This material is based upon work supported by the Department of Energy under Award Number(s) DE-FE0026308."

SWRO + HPRO Hybrid Technoeconomics Summary

Base Case 2x SWRO System for Comparison to Hybrid SWRO + HPRO System



200 GPM

Total Permeate
400 GPM

445 GPM/35k TDS

SWRO

245 GPM/63k TDS

35k TDS Feed
890 GPM

200 GPM

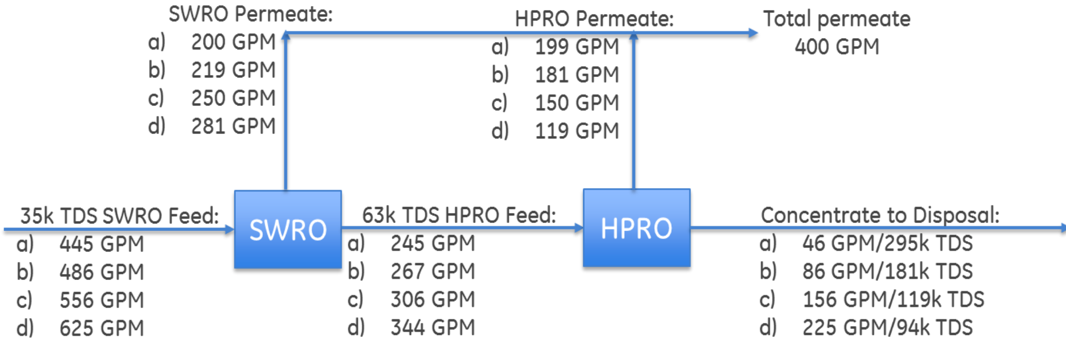
Concentrate to Disposal:
490 GPM/63k TDS

SWRO

445 GPM/35k TDS

245 GPM/63k TDS

Hybrid SWRO + HPRO System Cases Studied



SWRO Permeate:
a) 200 GPM
b) 219 GPM
c) 250 GPM
d) 281 GPM

HPRO Permeate:
a) 199 GPM
b) 181 GPM
c) 150 GPM
d) 119 GPM

Total permeate
400 GPM

35k TDS SWRO Feed:
a) 445 GPM
b) 486 GPM
c) 556 GPM
d) 625 GPM

SWRO

63k TDS HPRO Feed:
a) 245 GPM
b) 267 GPM
c) 306 GPM
d) 344 GPM

HPRO

Concentrate to Disposal:
a) 46 GPM/295k TDS
b) 86 GPM/181k TDS
c) 156 GPM/119k TDS
d) 225 GPM/94k TDS

Normalized Cost of Hybrid SWRO + HPRO System Cases Studied

Case	System Feed Flowrate (GPM)	System Concentrate Flowrate (GPM)	System Concentrate TDS (mg/L)	Normalized Cost*
(a)	445	46	295,000	0.90
(b)	486	86	181,000	0.76
(c)	556	156	119,000	0.82
(d)	625	225	94,000	0.91

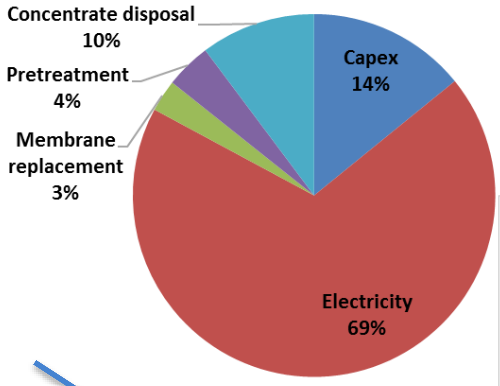
*Normalized cost = (hybrid SWRO + HPRO system cost)/(2x SWRO system cost); cost per m3 product water

HPRO Feed Pressure and Concentrate Concentration

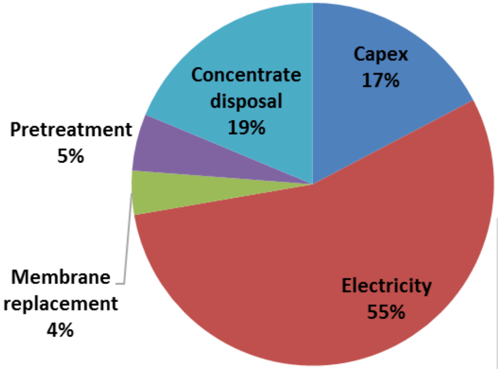
Case	HPRO Concentrate TDS (mg/L)	HPRO Operating Pressure (psi)
(a)	295,000	6800
(b)	181,000	3200
(c)	119,000	1900
(d)	94,000	1500

Costs included: SWRO/HPRO (Capex, Energy, Membrane Replacement), Pretreatment and Disposal

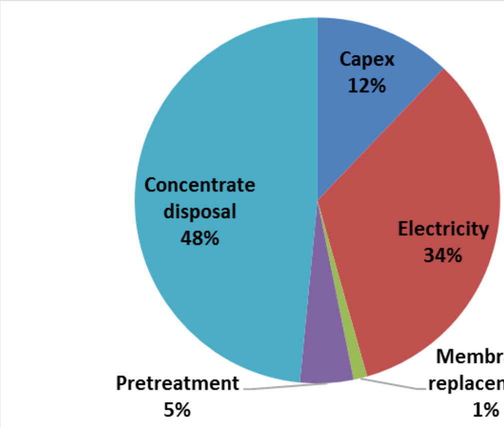
SWRO + HPRO Hybrid Cost Breakdown



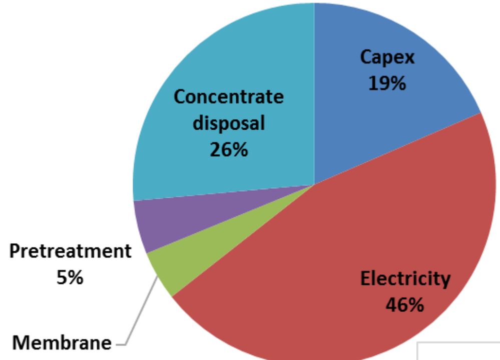
445 GPM



486 GPM

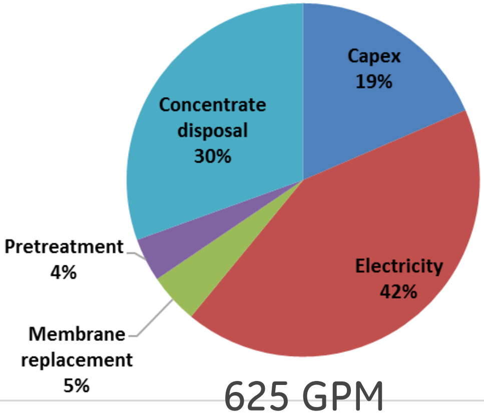


2x SWRO



556 GPM

↑ Capex
↑ Disposal
↓ Energy



625 GPM

Increasing SWRO + HPRO system size:

- More permeate production from SWRO
- Lower recovery required of HPRO
- More concentrate remaining for disposal

TEM details

Opex

- Key Assumption:

– Flux linear with pressure

Capex

- High pressure system estimate:[1]

$$C_V = C_B F_t \,(B_1 + B_2 F_M F_P) F_C$$

- Base cost: SeaPRO-84 cost
- Key assumption:

– HPRO system has same flowrates, number of elements & housings as SeaPRO system

ID	Definition
C_V	High pressure component cost
C_B	Base component cost
F_t	Time factor (assumed = 1 b/c base cost quoted 7/2016)
F_M	Material factor (for corrosion resistance)
F_P	Pressure factor (material thickness for high pressure)
F_C	Corrosion factor (additional thickness to allow for corrosion rate over system lifetime; assumed = 1 but needs to be included)

- Ongoing improvements:
  - Quotes for high cost components (pumps, ERDs, pressure gauges, controls (VFD)) to validate factored estimate approach
  - Element cost estimate from components
  - Account for corrosion (F_C)
  - Use real (not ideal) membrane performance (i.e., with compaction)

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[1] *Ulrich, G. D., and P. T. Vasudevan, Chemical Engineering Process Design & Economics: A Practical Guide, Second Edition, 2004.*