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Salinity gradient energy: Assessment of pressure retarded osmosis and osmotic heat engines for energy generation from low-grade heat sources

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EARTH ENERGY ENVIRONMENT

Salinity gradient energy: Assessment of pressure retarded osmosis and osmotic heat engines for energy generation from low-grade heat sources

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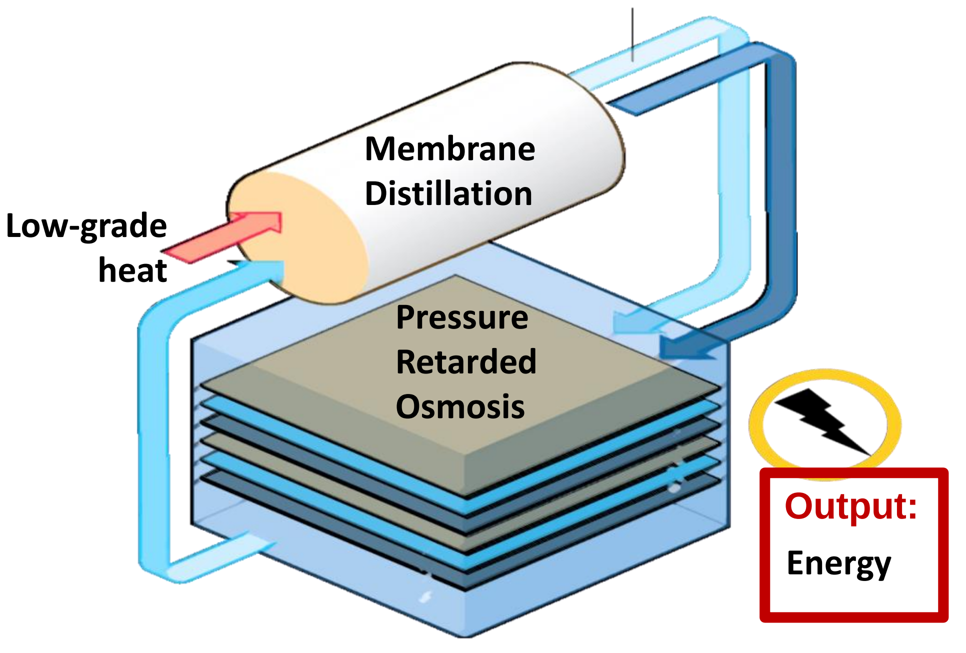
Structure of the Presentation



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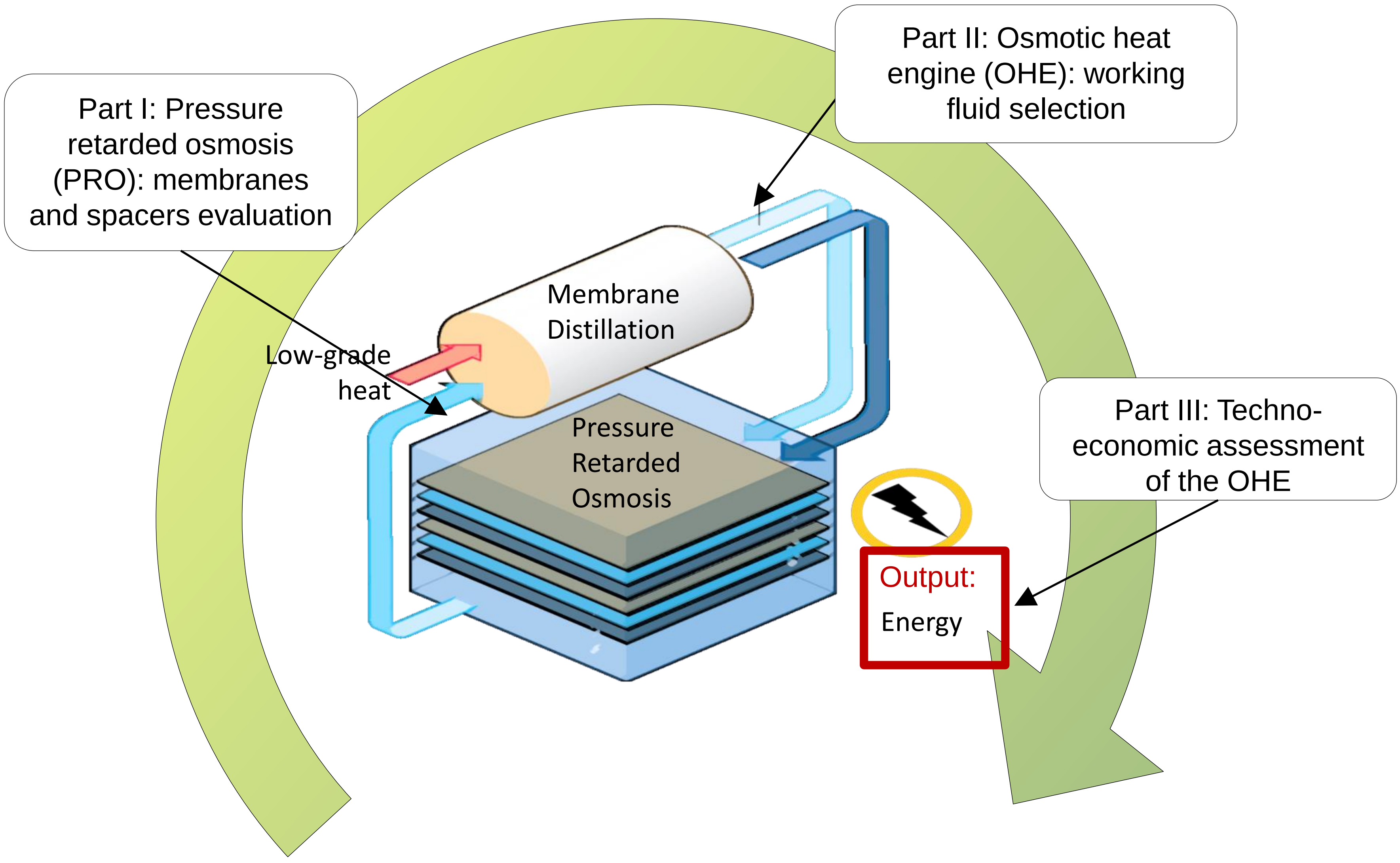
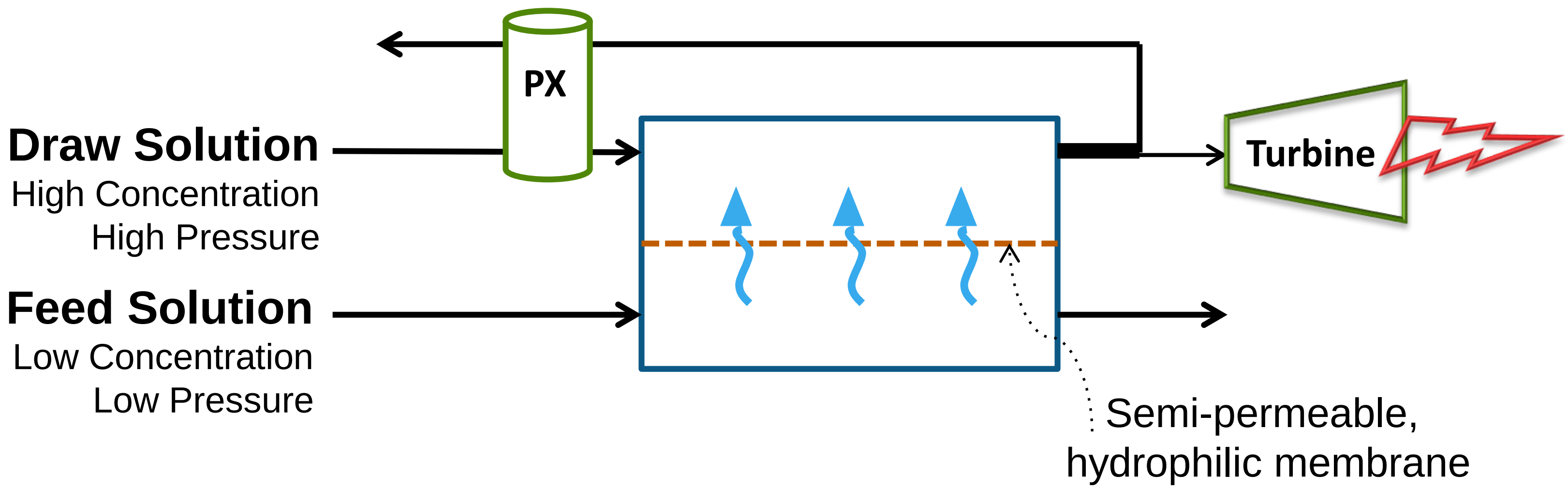


Pressure Retarded Osmosis (PRO): Utilizing Energy from the Ocean



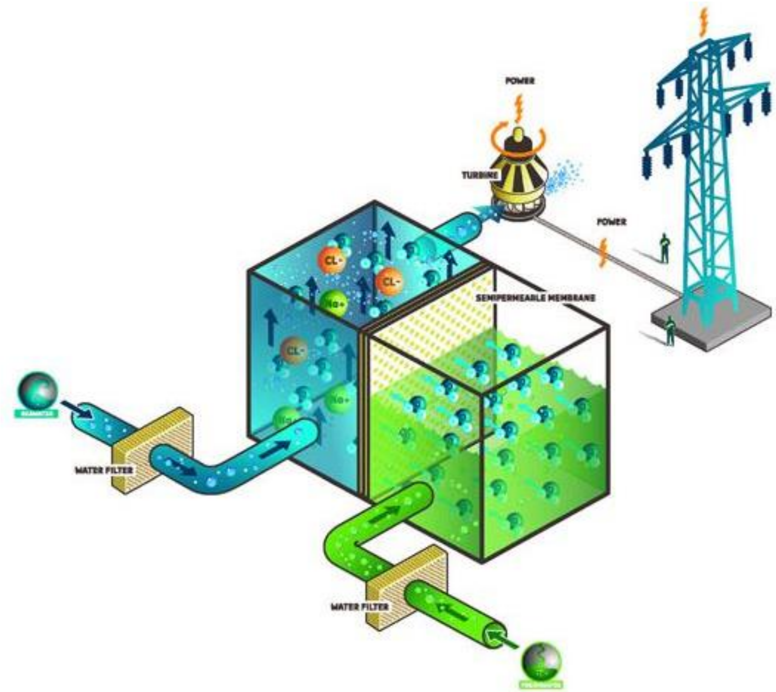
Applied Pressure < Osmotic Pressure

Water Flux (J_w) = A($\Delta\pi$-ΔP) (simplistic!)

Power Density (W) = $J_w \Delta P$ (power output per membrane area)

Open-Loop PRO

- Applications
  - Seawater – River water
  - RO concentrate – freshwater
  - Dead Sea and Great Salt Lake
- Limitations of open loop PRO
  - Extensive pretreatment needed
  - Potential irreversible membrane fouling
  - Solution chemistry and temperature are fixed

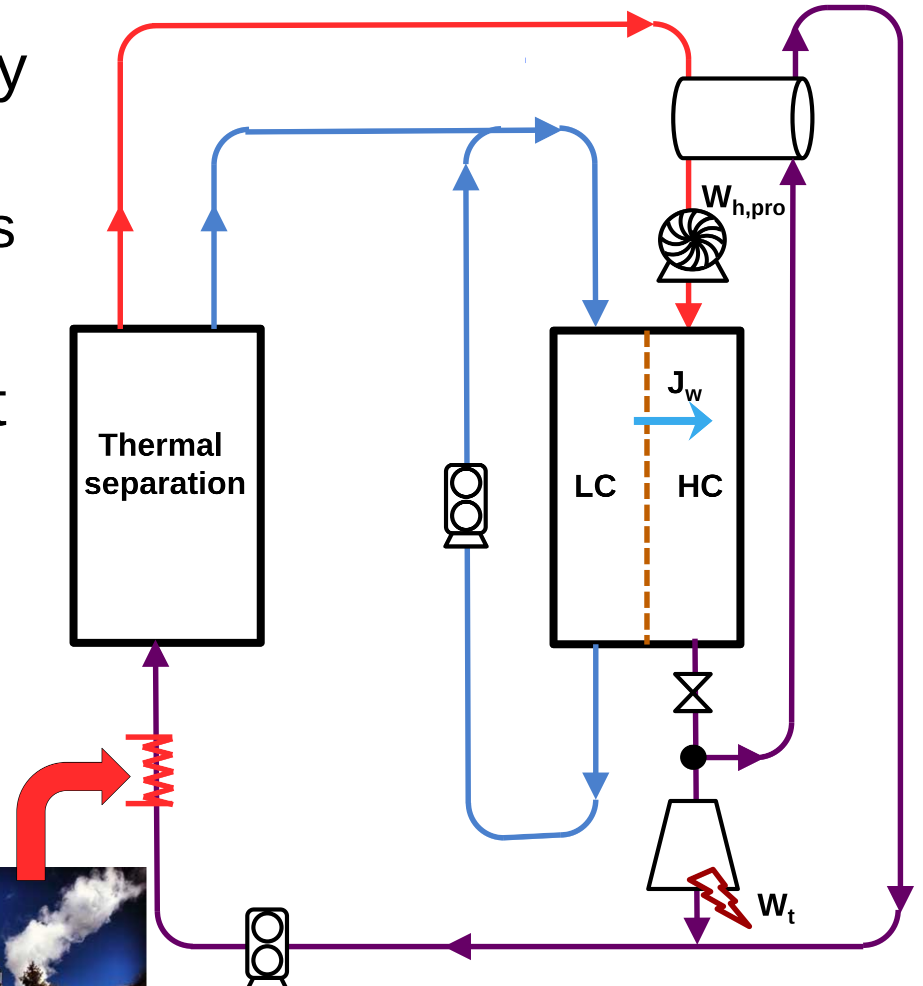


Source: Statkraft

Closed-Loop PRO: Osmotic heat engine (OHE)

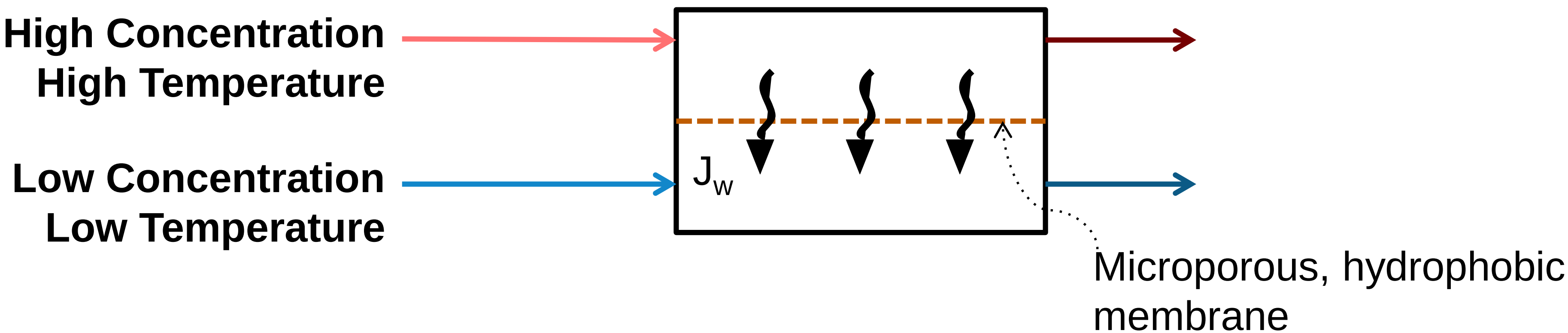
- Controlled solution temperature and chemistry
  - High osmotic pressures yields high power densities
  - Lower reverse salt flux
- Can utilize low-grade heat
- Potential for energy storage

Closed loop system =
No backwashing or
chemical cleaning!



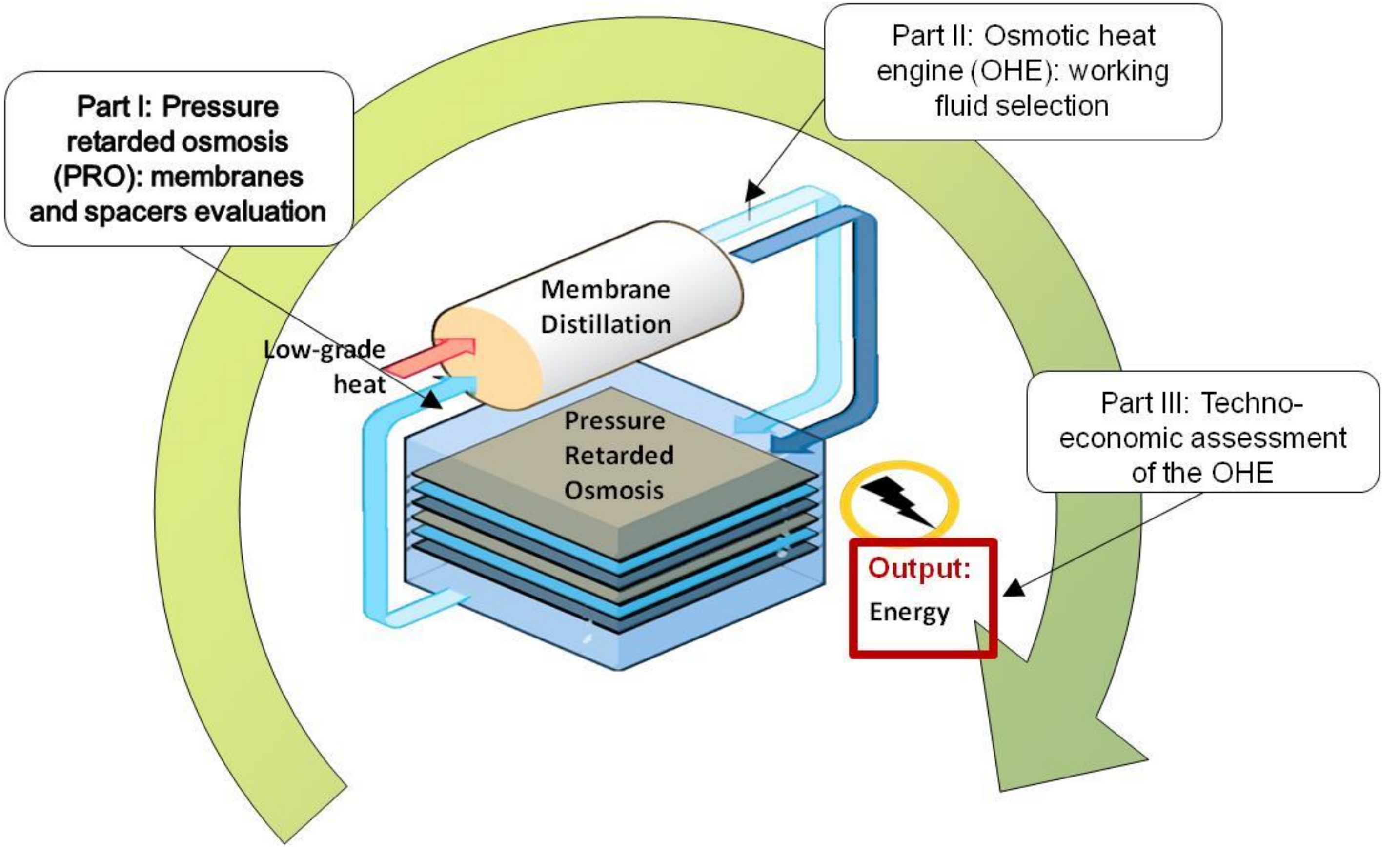
HC = high concentration (DS)
LC = low concentration (DI water)

Membrane Distillation (MD): Utilizing LGH for Draw Solution and Feed Stream Regeneration



Water Flux (J_w) = $A_w(\Delta P_v{}^*)$ (simplistic!)

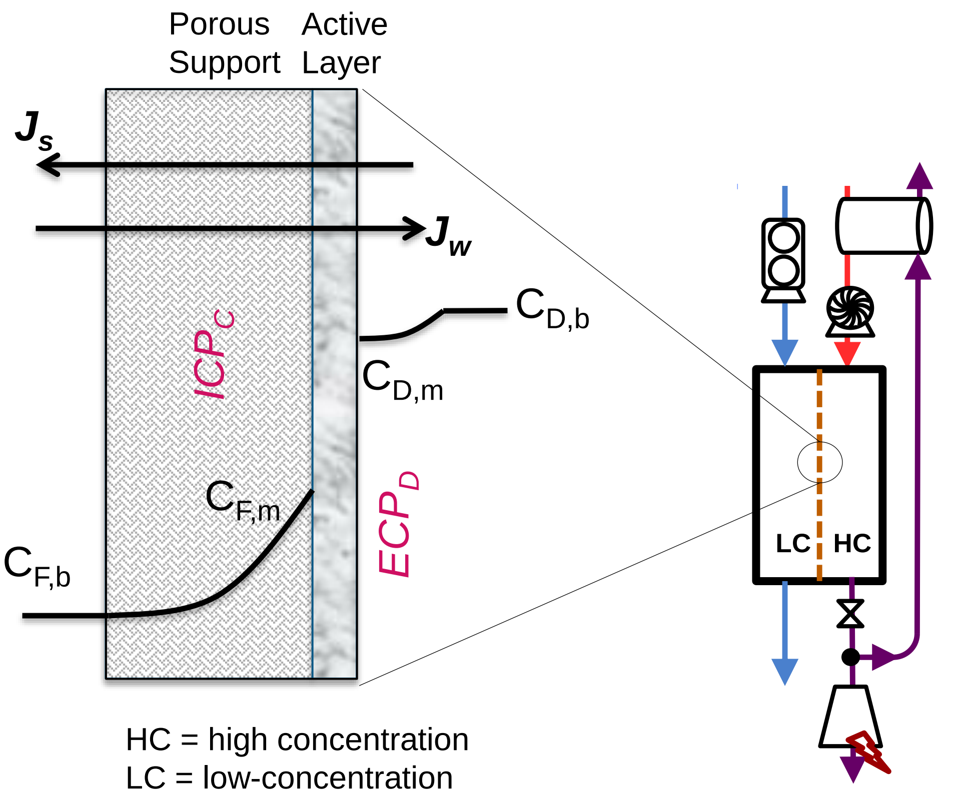
Can utilize low-grade heat to simultaneously separate and concentrate mixed streams



PRO MEMBRANE AND SPACER ASSESSMENT

PRO: An Energy Generating Membrane Process

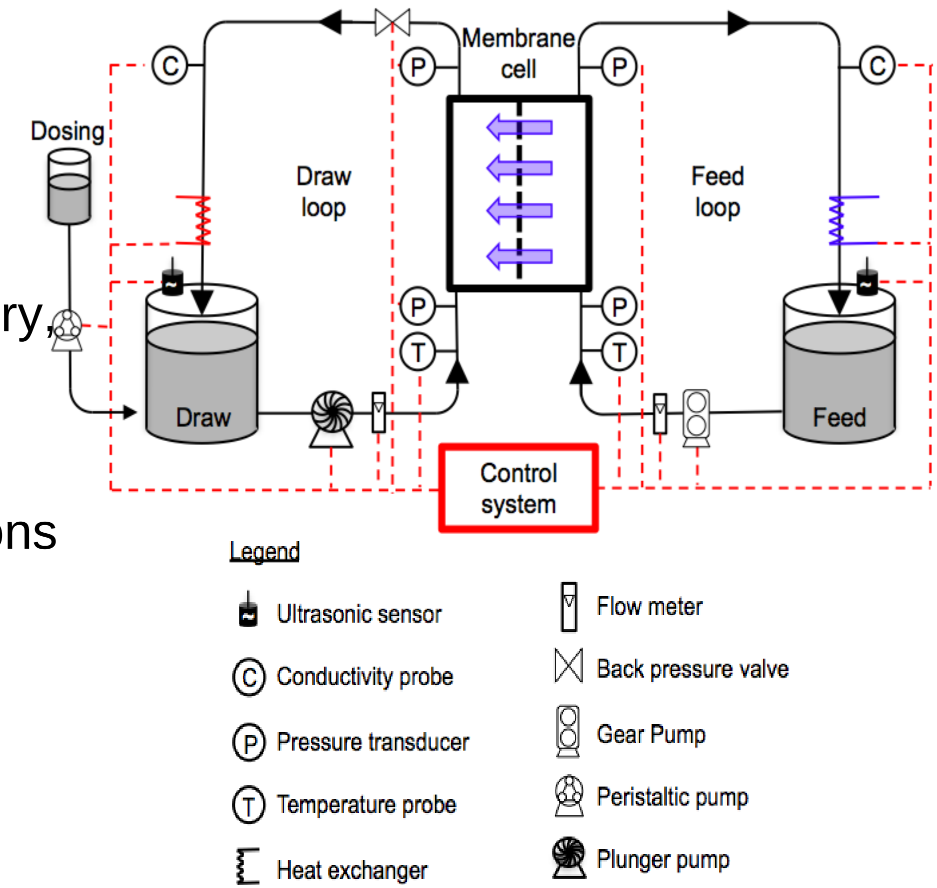
- PRO membranes are not yet commercially available and FO membranes are used
- PRO membranes must:
  - Exhibit high power density & low reverse solute flux
  - Withstand high operating pressures
- PRO membrane spacers must provide good mixing and adequate support



HC = high concentration
LC = low-concentration
$C_{D,b}$ = bulk draw concentration
$C_{D,m}$ = membrane interface draw conc.
$C_{F,b}$ = bulk draw concentration
$C_{F,m}$ = membrane interface draw conc.
ECP_{dil} = dilutive external CP
ICP_C = concentrative external CP

Operating Conditions: PRO

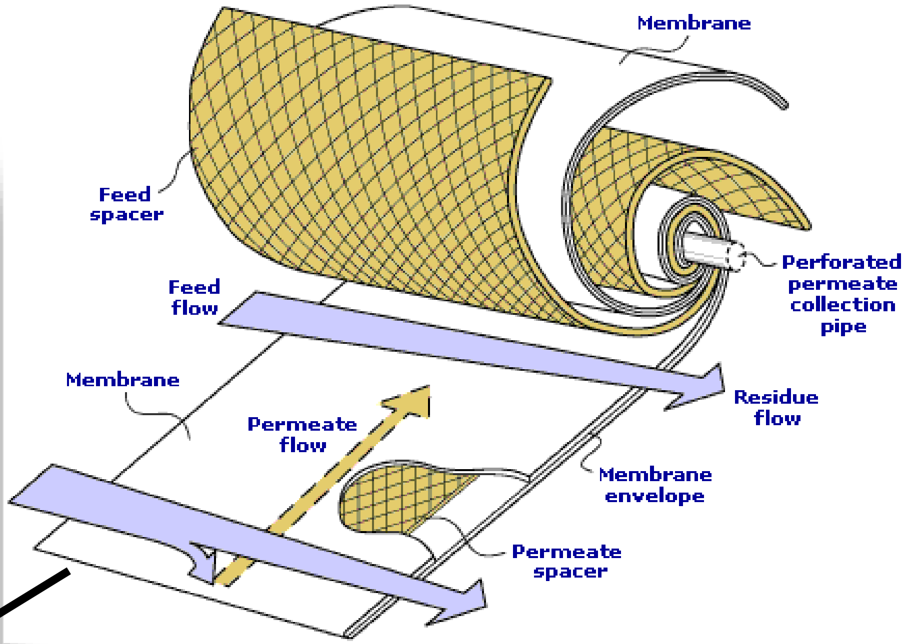
- Source water
  - Draw solution (DS): 1, 2, & 3 M NaCl
  - Feed: deionized water
- Bench scale testing
  - SCADA system controls temperatures, and collect data to calculate water flux, batch recovery, and salt rejection
- Flat sheet FO membranes
  - Hydration Technologies Innovations (HTI) thin-film composite (TFC)
  - HTI cellulose triacetate (CTA)
  - Oasys Water TFC
  - X company TFC



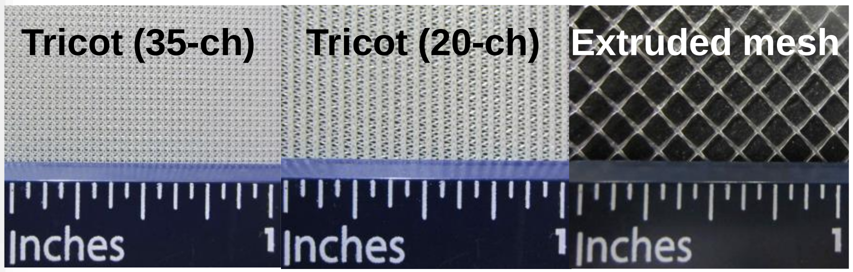
PRO Bench-Scale System

PROzilla

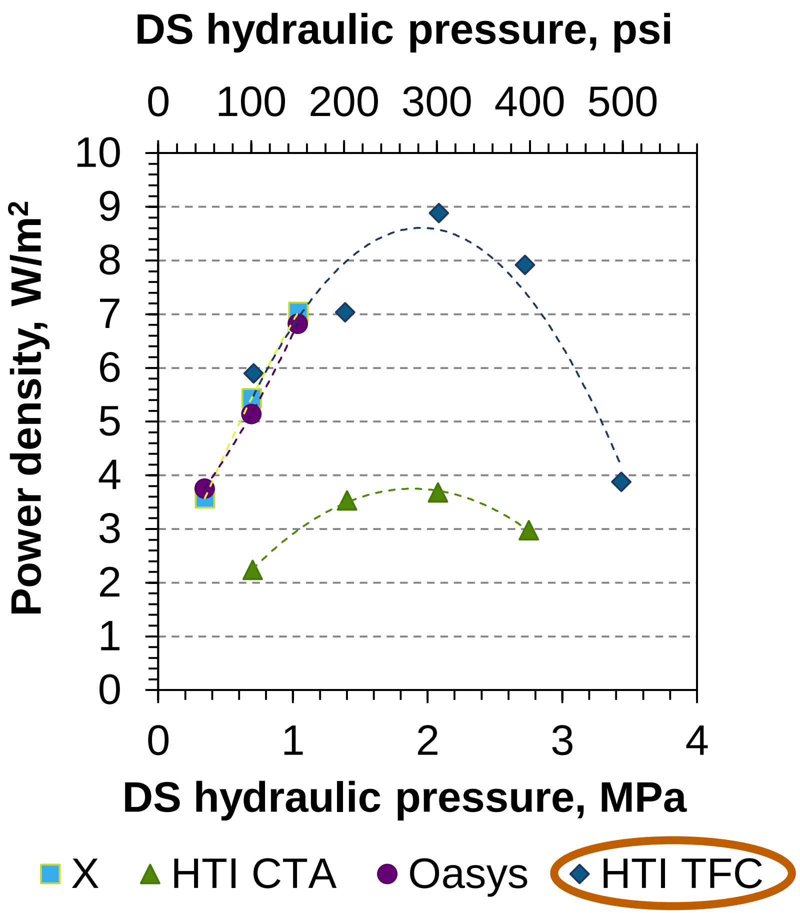
Membrane module

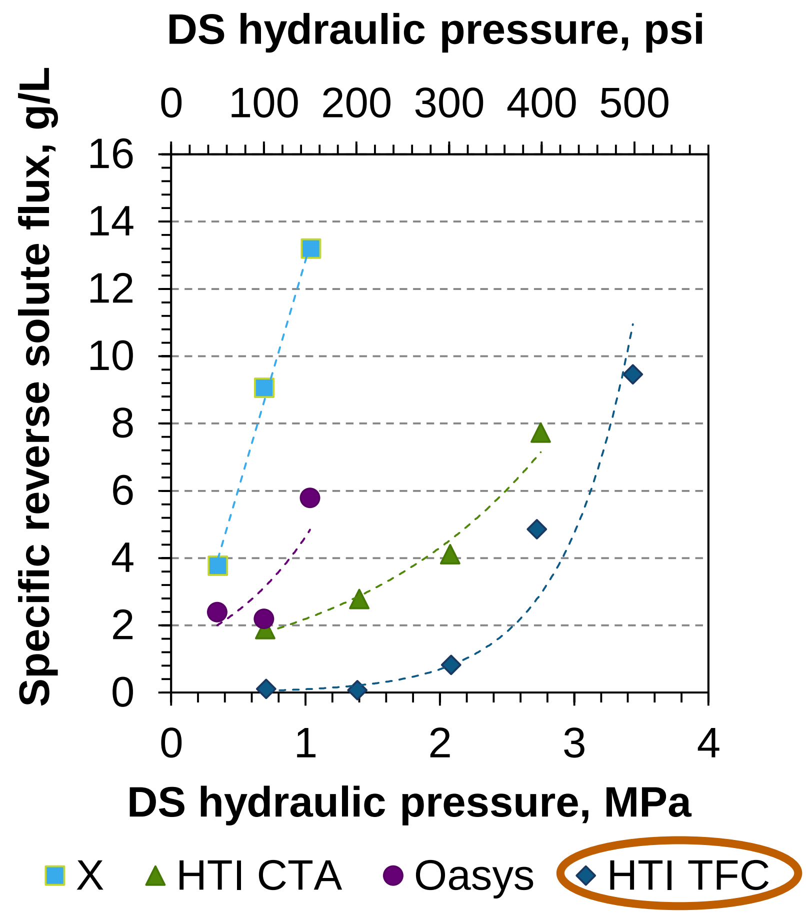


Membrane spacers



PRO Membrane Evaluation:





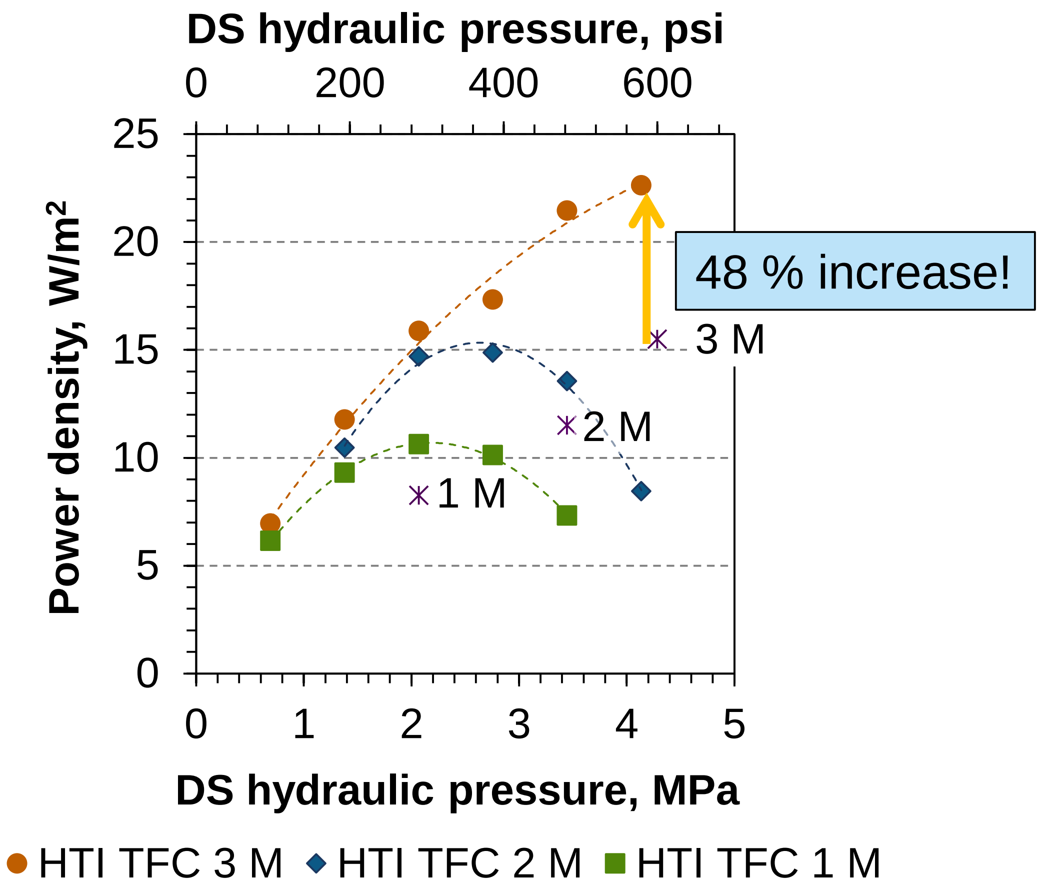
✓ High power densities

1 M NaCl draw solution (DS); 2x – 20 channel tricot on feed

✓ Low specific reverse solute flux

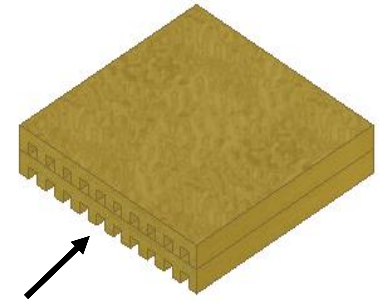
✓ Good mechanical stability

Spacer Orientation

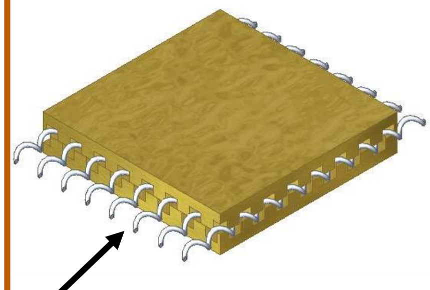


Feed spacer orientations

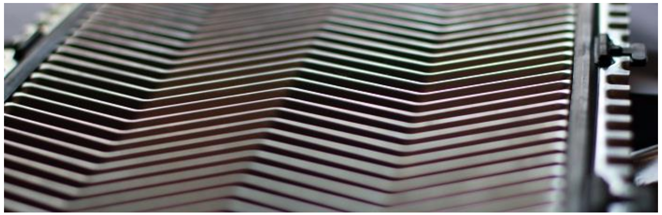
Parallel to flow



45° to flow



Corrugated heat exchanger plate

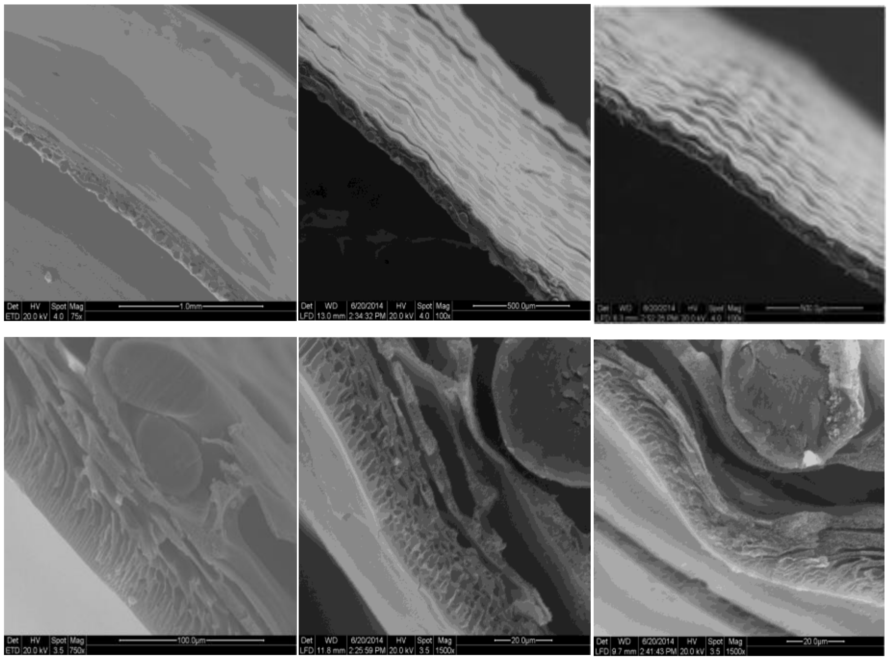


Spacerless patterned membranes!

Membrane Deformation

Surface

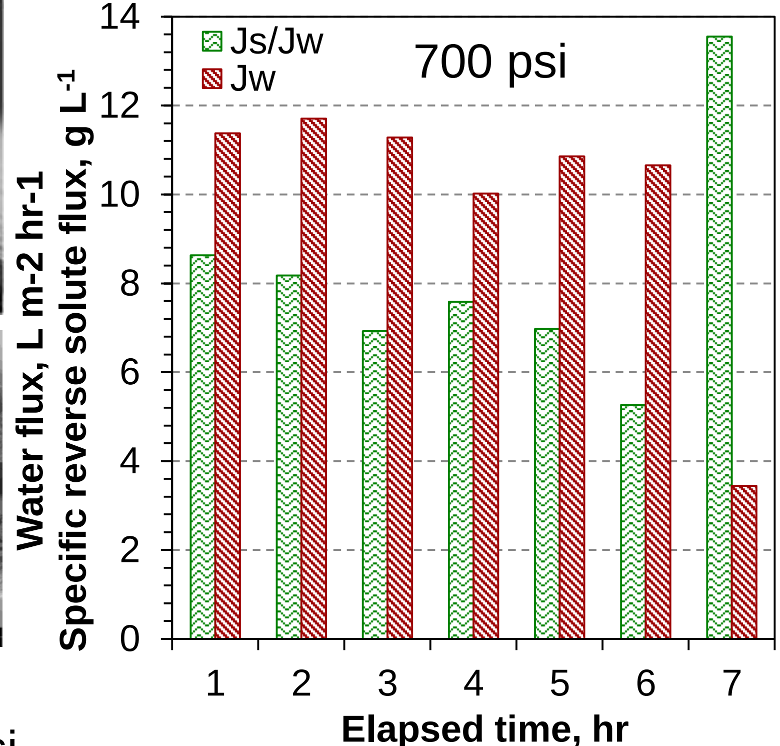
Cross-section



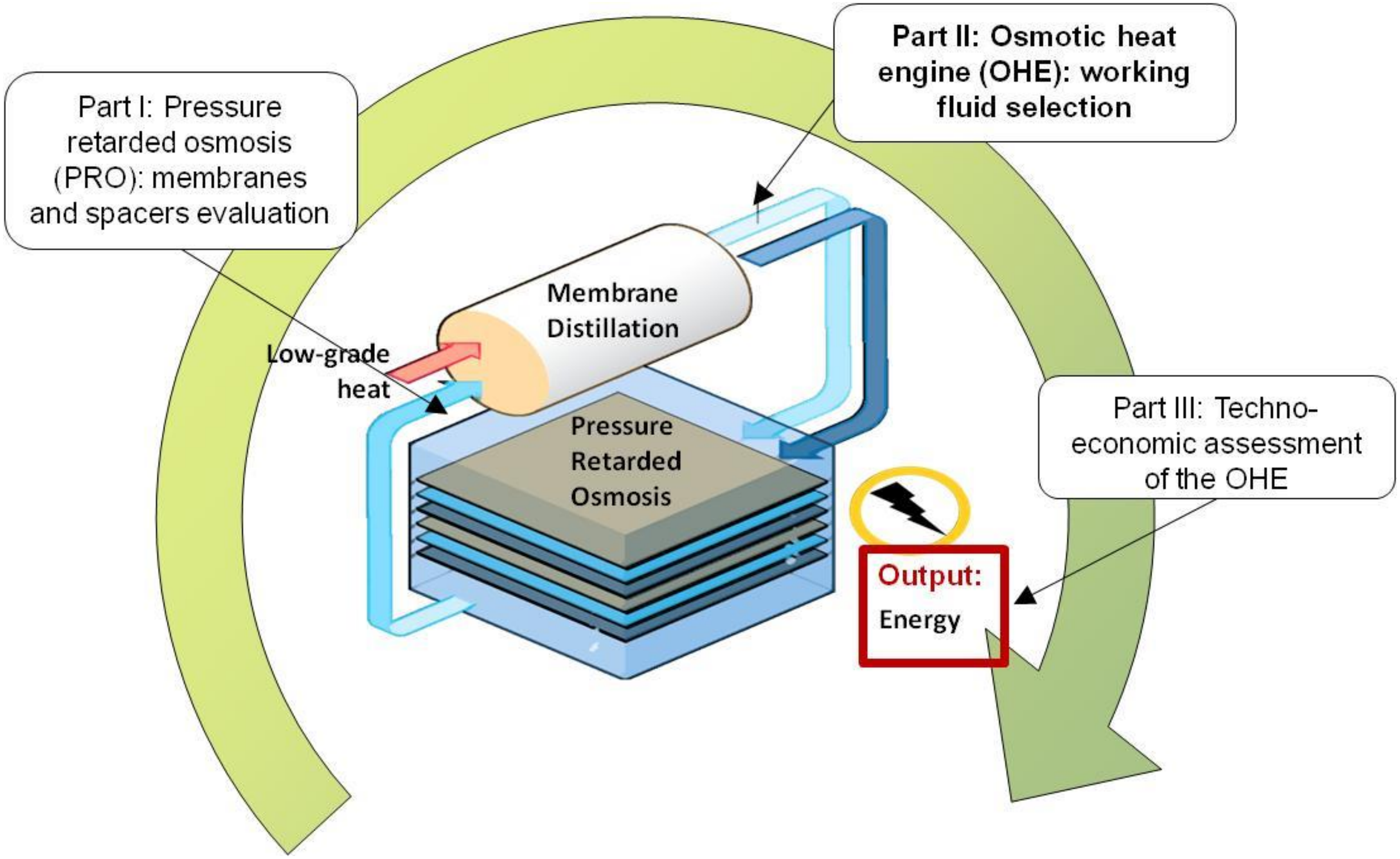
Virgin membrane

Membrane after 450 psi

Membrane after 600 psi



Importance of long term experiments!!!



OHE WORKING FLUID SELECTION

Reverse Solute Flux in PRO and Implications for OHE Process Performance

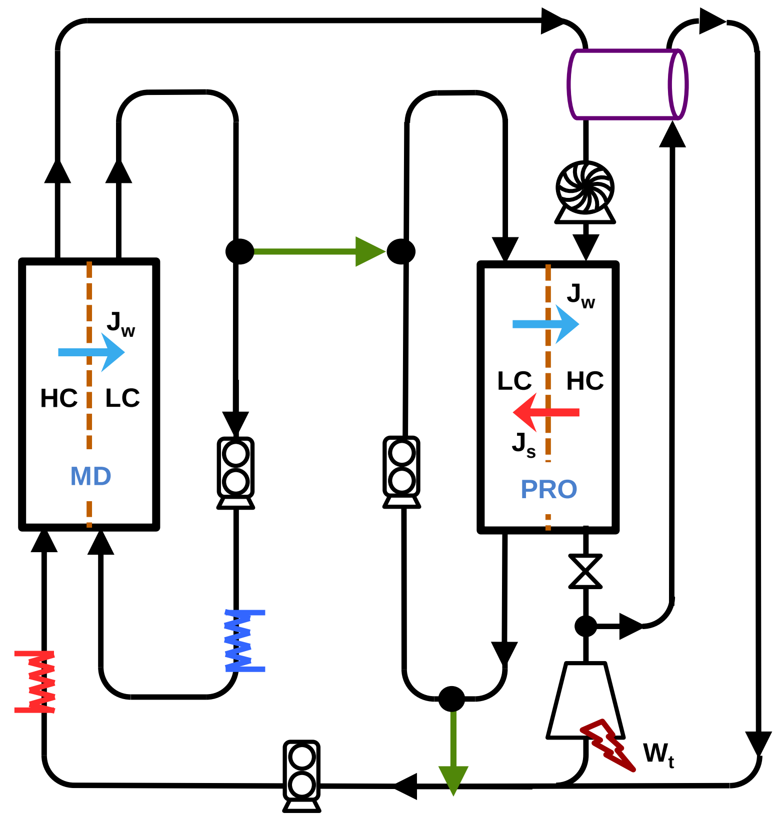
- Non-idealities in PRO gives rise to reverse solute flux (RSF, J_s):

$$J_s = B\left\{\frac{\pi_{D,b}\exp\left(-\frac{J_w}{k}\right) - \pi_{F,b}\exp\left(J_w\frac{S}{D}\right)}{1+\frac{B}{J_w}\left[\exp\left(J_w\frac{S}{D}\right)-\exp\left(-\frac{J_w}{k}\right)\right]}\right\}$$

$$J_w = A\left\{\frac{\pi_{D,b}\exp\left(-\frac{J_w}{k}\right) - \pi_{F,b}\exp\left(J_w\frac{S}{D}\right)}{1+\frac{B}{J_w}\left[\exp\left(J_w\frac{S}{D}\right)-\exp\left(-\frac{J_w}{k}\right)\right]} - \Delta P\right\}$$

  - To sustain osmotic driving force, must bleed a portion of the PRO feed stream to the MD feed

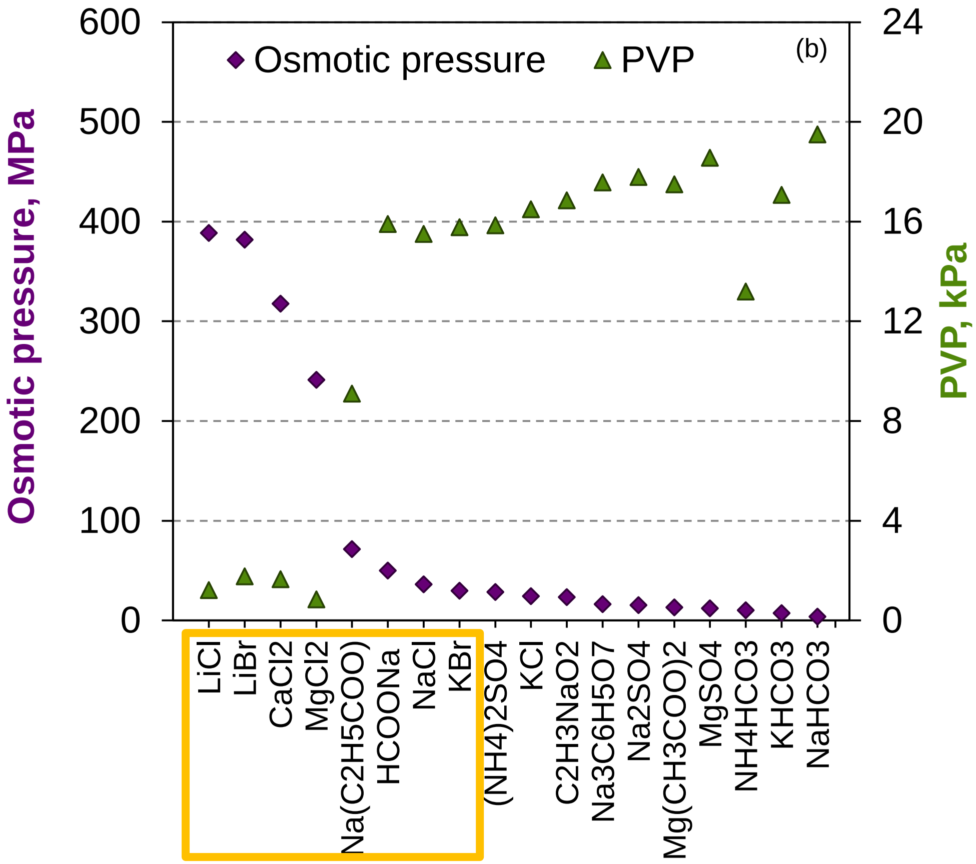
- Impacts of RSF on net power outputs and generation costs are unknown!



Legend:

π = osmotic driving force
k = mass transfer coefficient (DS side)
S = membrane structural parameter
B = solute permeability coefficient
D = draw solution diffusivity

Draw Solution Screening and Selection

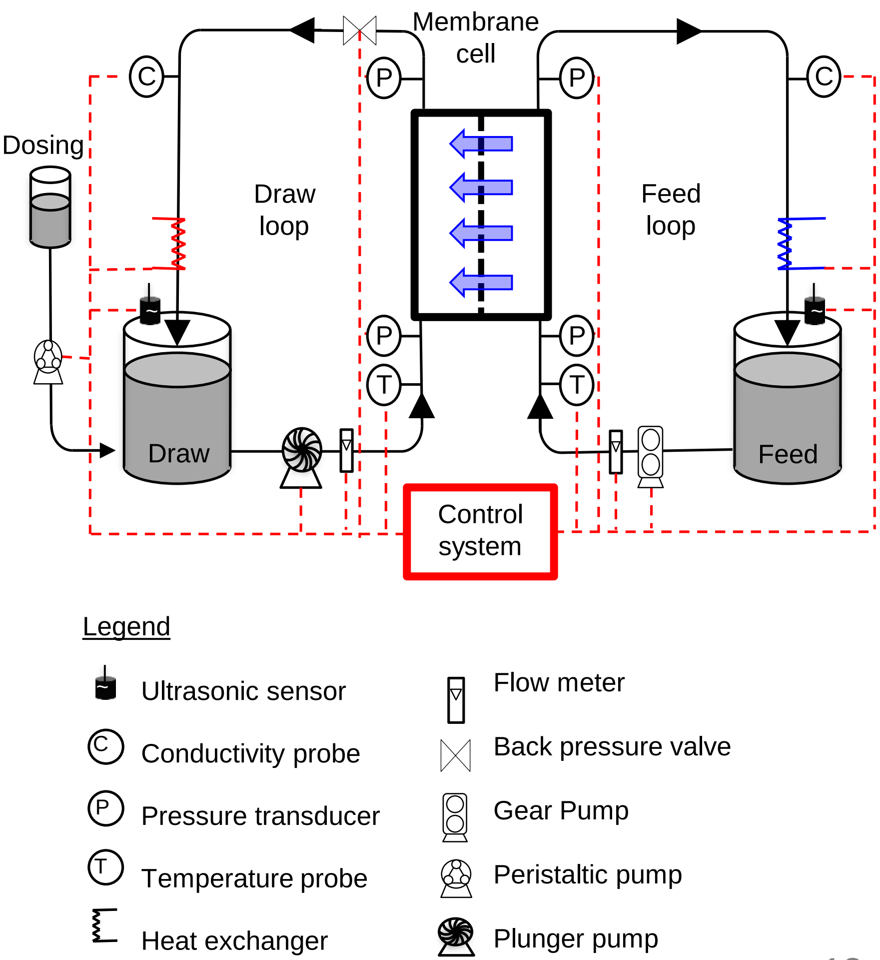


Draw solution	Cost $/kg	Concentration M
$CaCl_2$	83	1.6
HCOONa	14	4.1
KBr	42	3.2
LiBr	121	2.2
LiCl	74	2.6
$MgCl_2$	14	1.5
$Na(C_2H_5COO)$	38	4.1
NaCl	6	3.0

- Eight salts met screening criteria ($\pi > \pi_{NaCl}$ & non-hazardous)
- Tested at concentrations equivalent to 17.4 MPa osmotic pressure (osmotic pressure of 3 M NaCl)

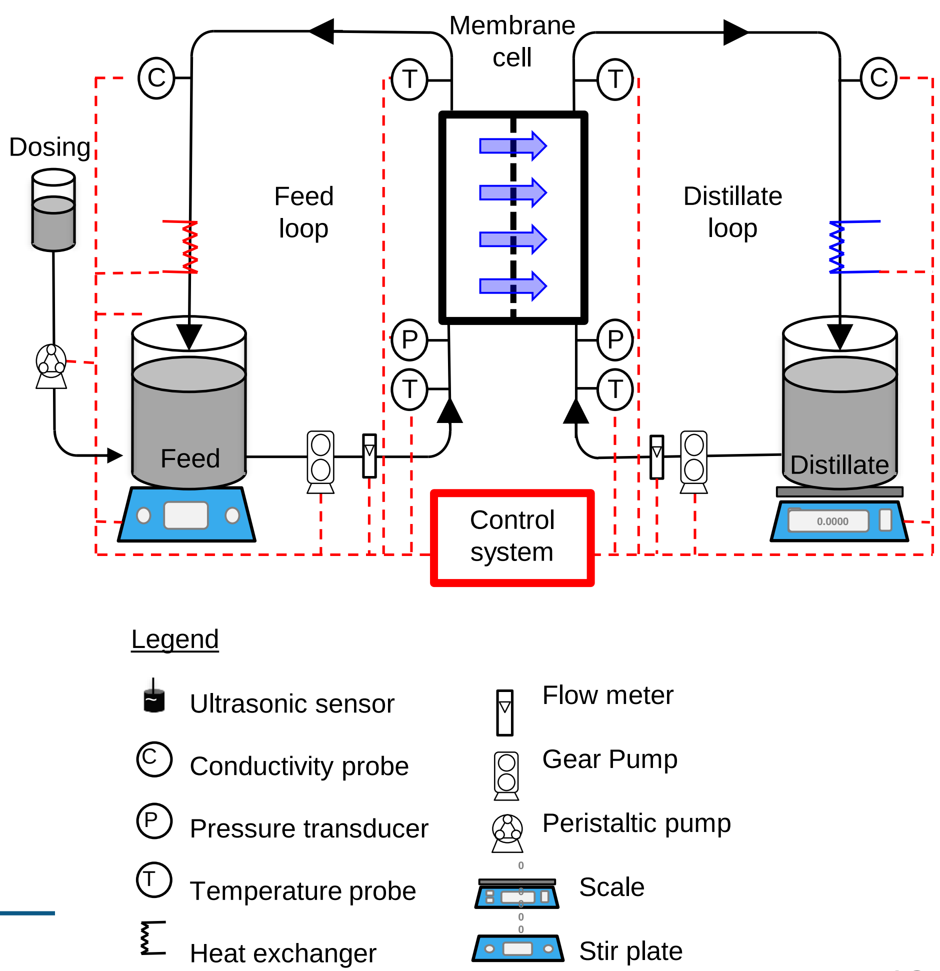
Operating Conditions: PRO

- Source water
  - Draw solution: varied, 30 ºC
  - Feed: deionized water, 30 ºC
- Membrane: HTI TFC
- Draw solution hydraulic pressure kept constant at 2 MPa (300 psi)

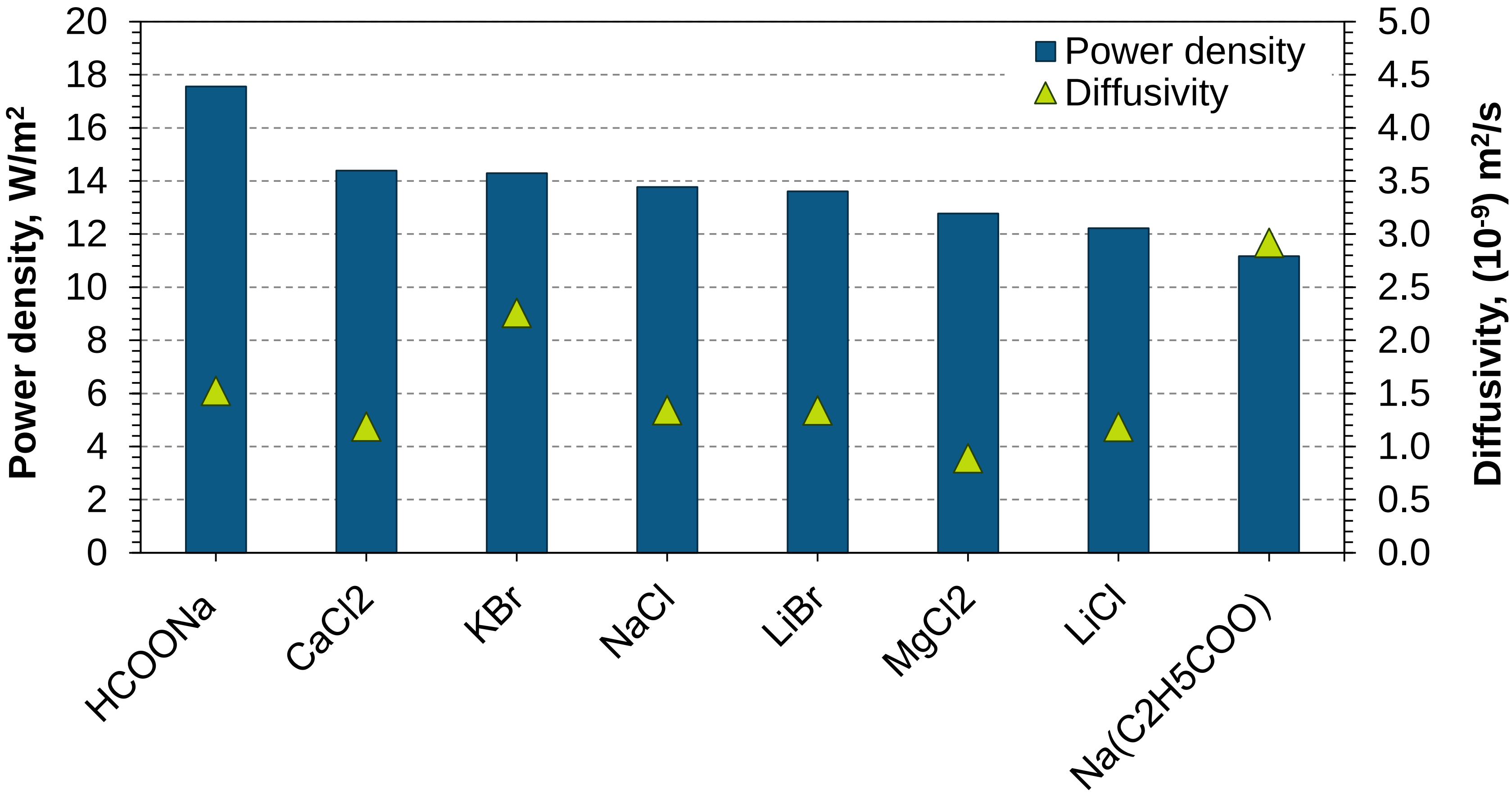


Operating Conditions: MD

- Source water
  - Feed solution: varied
    Distillate: deionized water
- Stream temperatures
  - Feed solution: 55 ºC
  - Distillate: 25 ºC
- Flat sheet, hydrophobic, microporous (0.2 μm) membranes from 3M

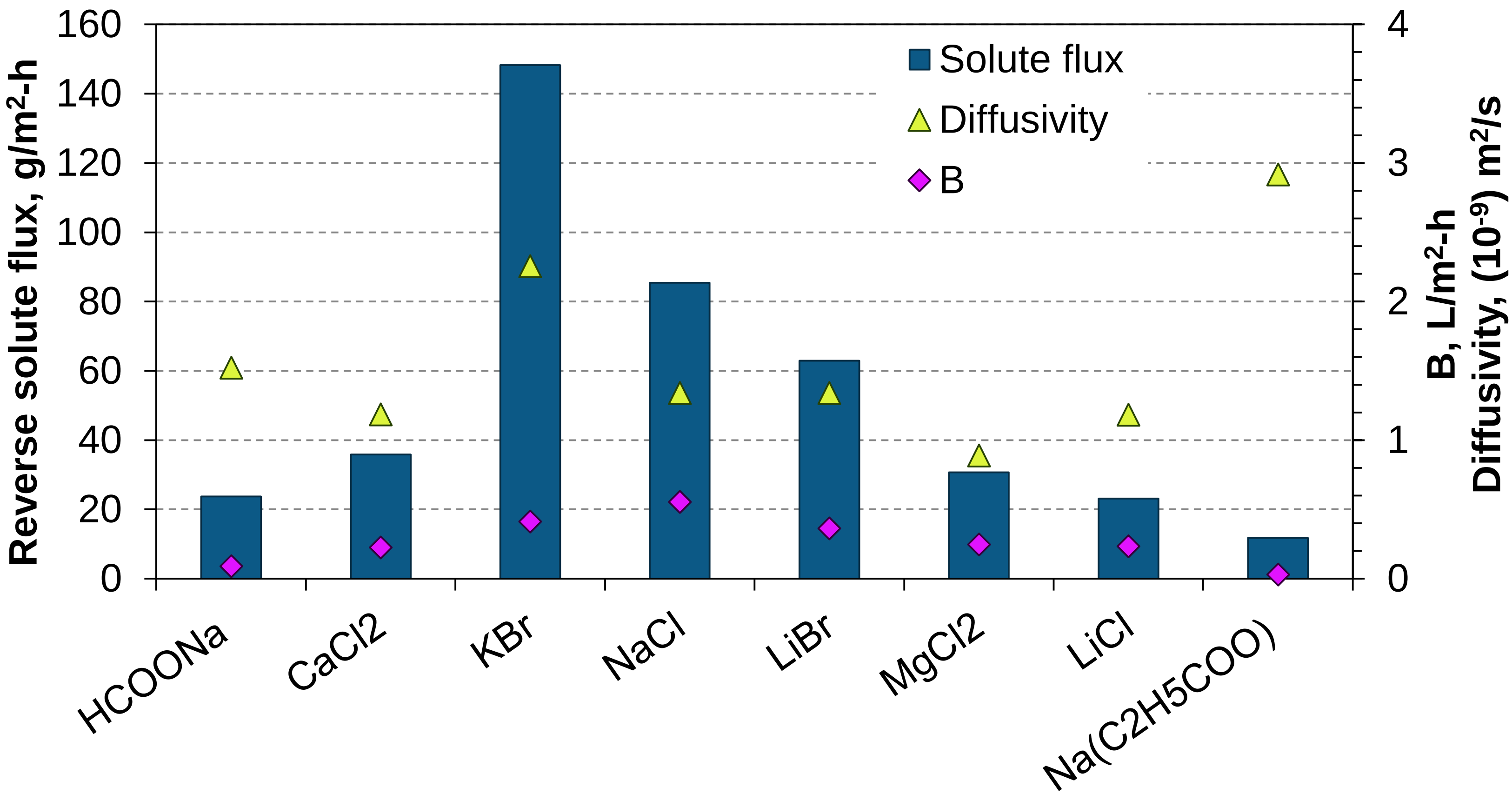


PRO Performance



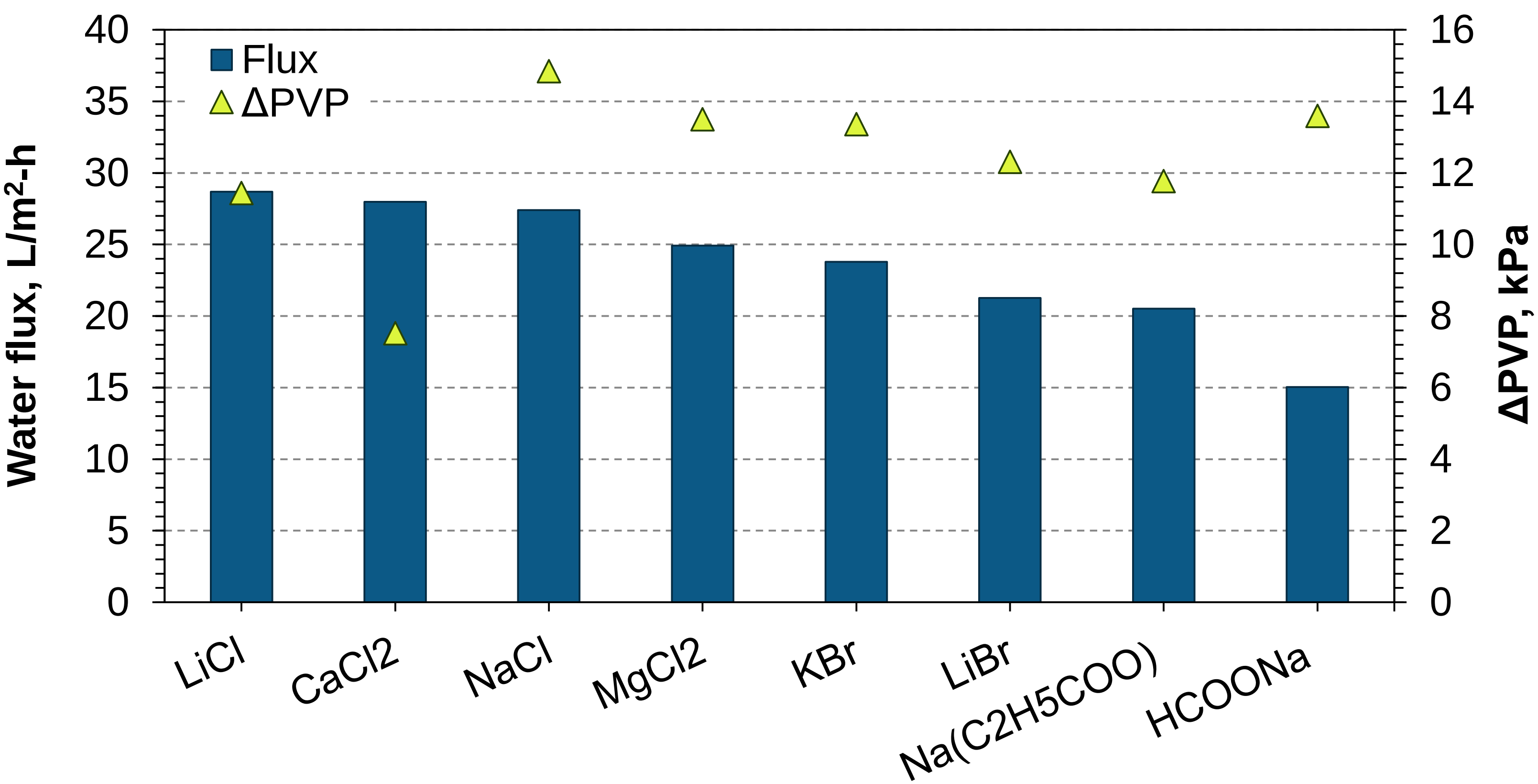
- Difference in power densities is because of the difference in diffusivity and solute permeability coefficient (B)

PRO Performance



- Higher diffusivities lead to higher reverse salt fluxes
- Salts with high reverse salt fluxes can be detrimental to system costs

MD Performance



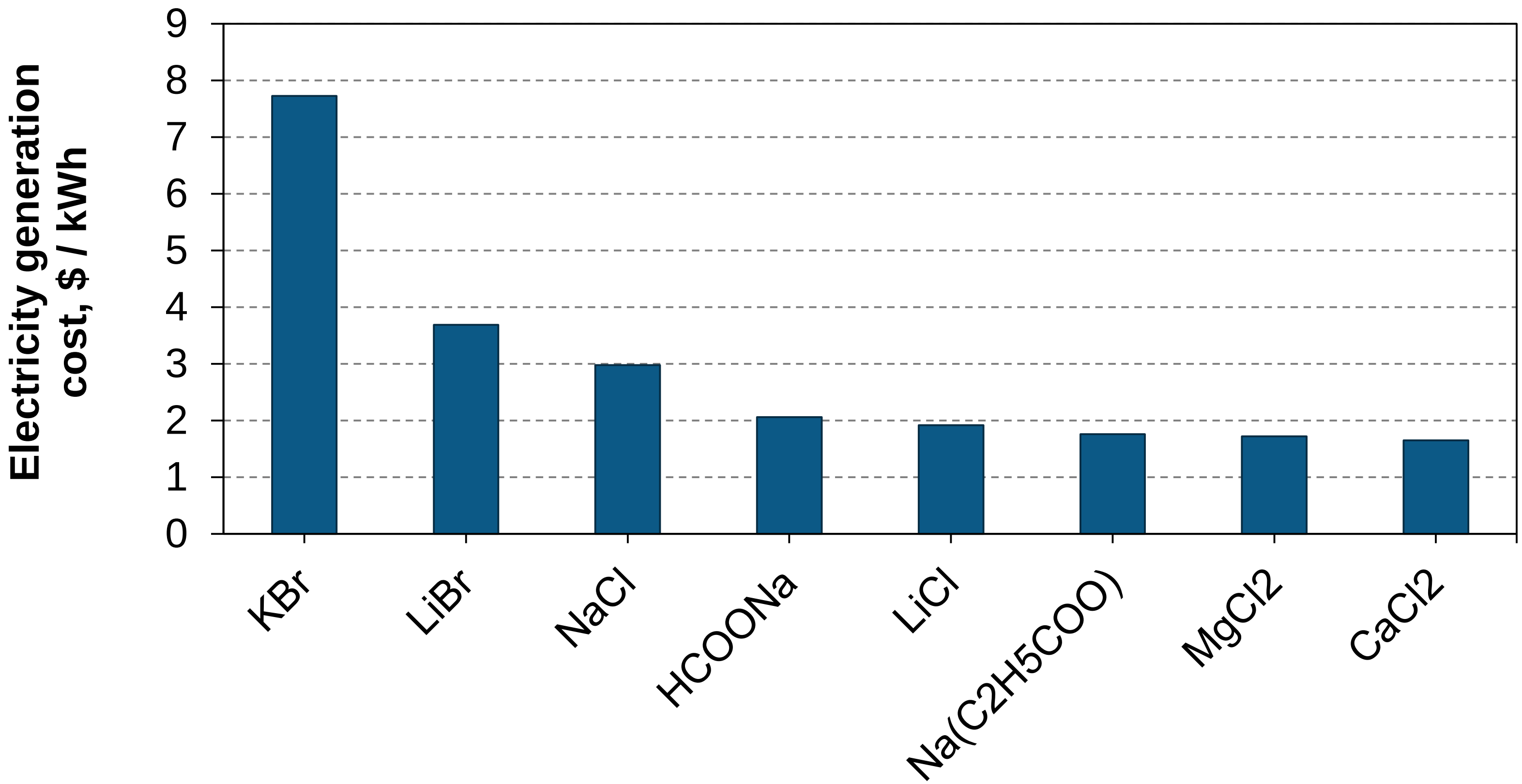
- Distillate conductivity decreased over time, indicating 100% rejection of salts
- Water flux decreases with decreased partial vapor pressure difference

Preliminary Economic Evaluation of Draw Solutions

- Experimental PRO and MD results were used in the model
- Design constraint: PRO feed concentration of 4 g/L (DS specific)
- Specific membrane and module costs for PRO and MD were referenced from RO and MF literature, respectively

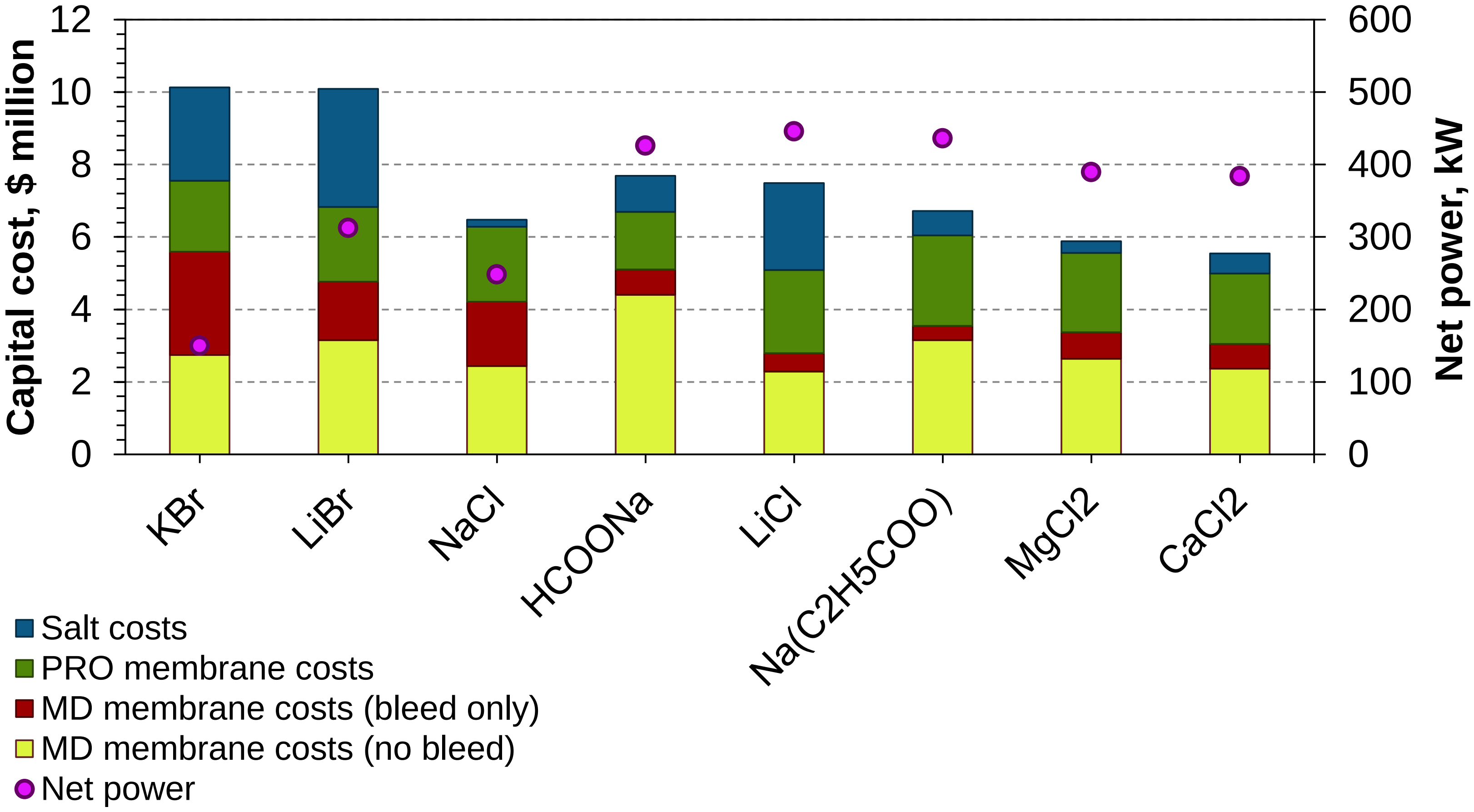
System operating parameters		
System size	1,000	kW
PRO operating inputs		
PRO water recovery	15%	
Applied hydraulic pressure (DS)	2 (300)	MPa (psi)
PRO module pressure drop	35 (5)	kPa (psi)
Feed temperature	30	ºC
Draw solution temperature	30	ºC
Draw solution concentration	Salt specific	$g\ L^{-1}$
Water flux	Salt specific	$L\ m^{-2}\ hr^{-1}$
Salt flux	Salt specific	$g\ m^{-2}\ hr^{-1}$
MD operating inputs		
Water recovery	6%	
PRO module pressure drop	14 (2)	kPa (psi)
Feed temperature	56 ± 2	ºC
Distillate temperature	25 ± 1.5	ºC
Draw solution concentration	Salt specific	$g\ L^{-1}$
Water flux	Salt specific	$L\ m^{-2}\ hr^{-1}$
Rejection	Salt specific	%
Specific costs		
Specific PRO membrane cost	28	$\$\ m^{-2}$
Specific MD membrane cost	38	$\$\ m^{-2}$
Equipment efficiencies		
ERD efficiency	95%	
Pump efficiency	70%	
Design Constraint		
PRO feed solution concentration	4	$g\ L^{-1}$ or less

Impact of Draw Solutions on System Costing



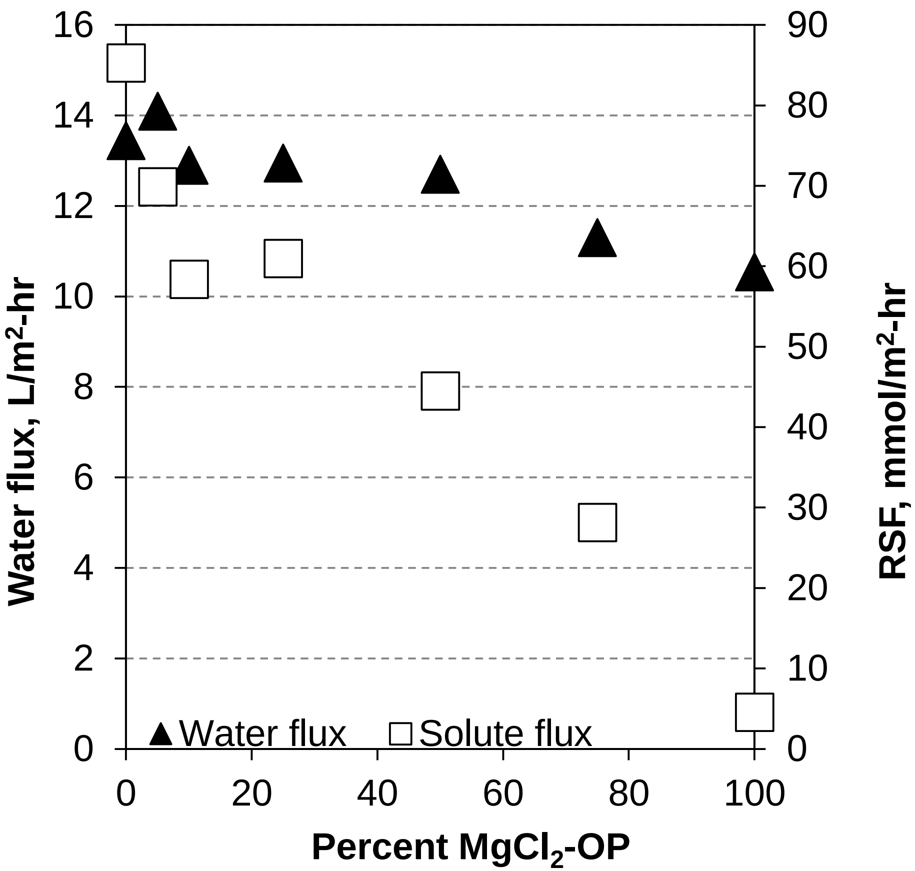
- $CaCl_2$ and $MgCl_2$ were the salts that performed best in MD and had the lowest specific reverse solute fluxes
- Electricity generation costs are higher than expected because of low PRO operating pressures (low power densities)

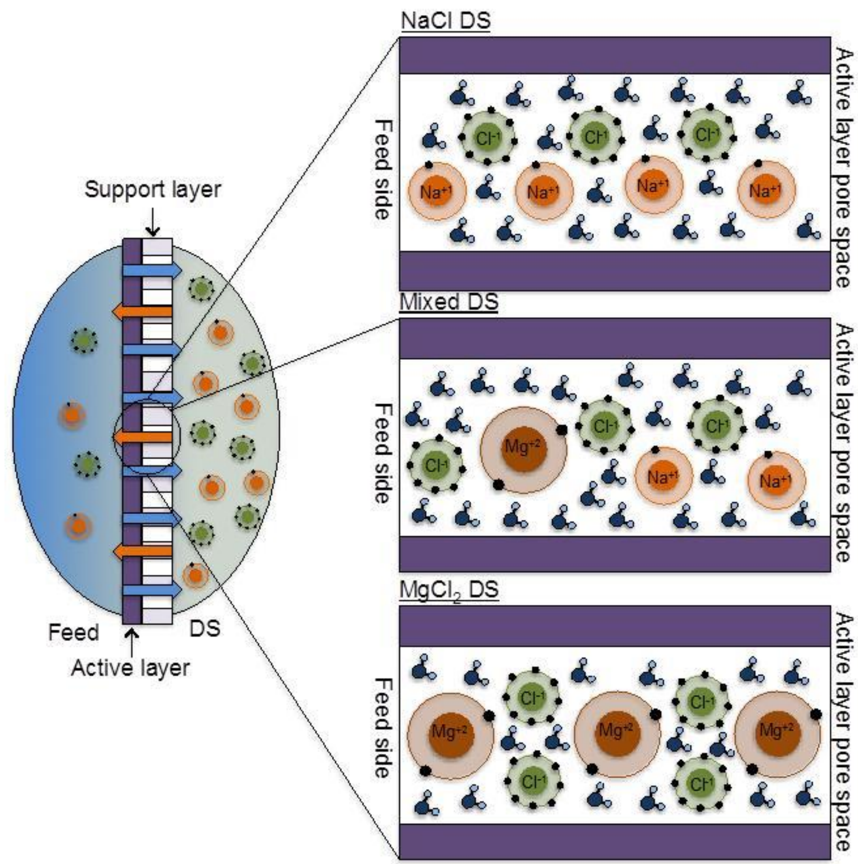
System Costing and Net Energy (1 MW gross)



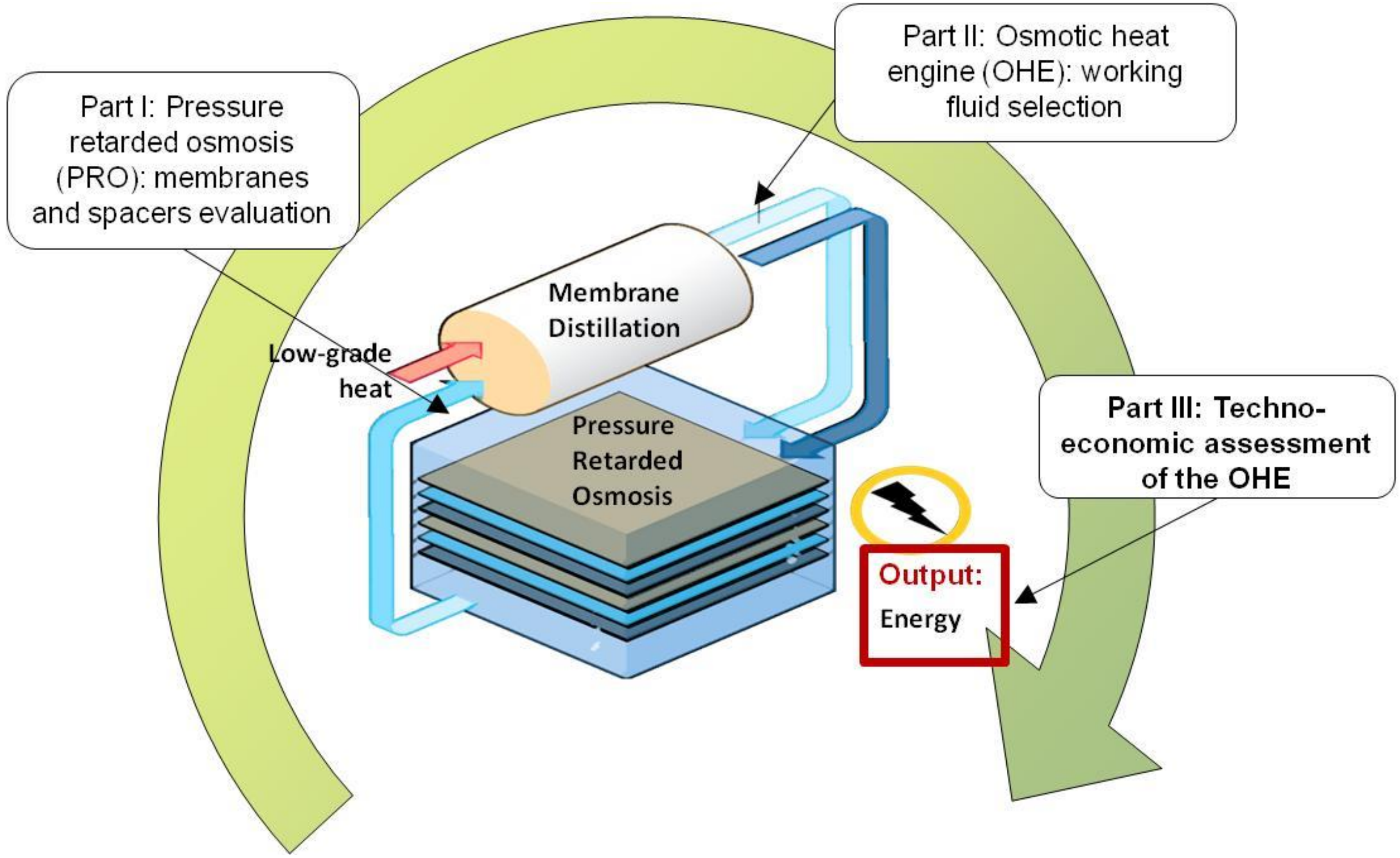
- MD membranes are the highest costs
- Salts with high RSF result in more bleeding, subsequently decreasing net energy and increasing MD membrane area

Mixed draw solutions: best of both worlds?





- With addition of $MgCl_2$, high water flux of NaCl can be maintained while RSF drops significantly



OHE TECHNO-ECONOMIC ASSESSMENT

OHE System Model and Cost Assumptions

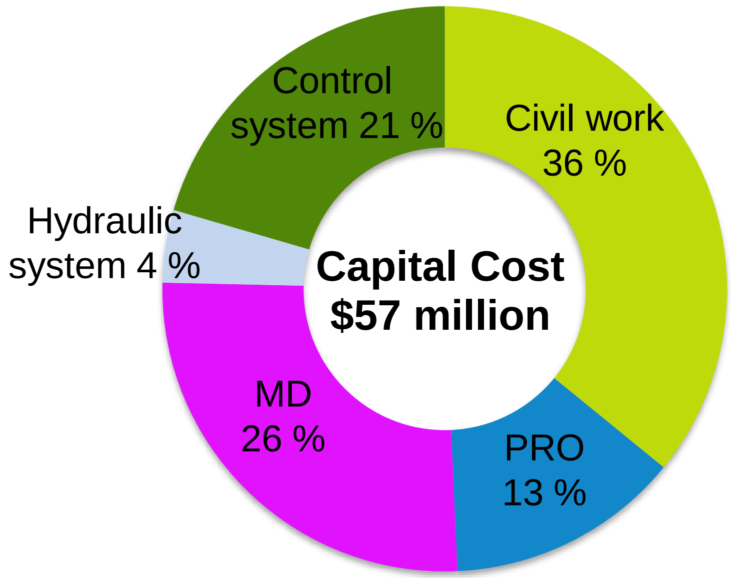
- Base case scenario
  - 2.5 MW (net power) system
  - Draw solution: 3 M NaCl
  - PRO operating pressure: 3.4 MPa (~500 psi)
  - MD temperatures: 70 ° C feed, 30 ° C distillate
- Assumptions
  - Low grade heat and cooling is free
  - Membrane costs referenced from commercially available membranes
    - PRO costs referenced from RO
    - MD costs referenced from MF

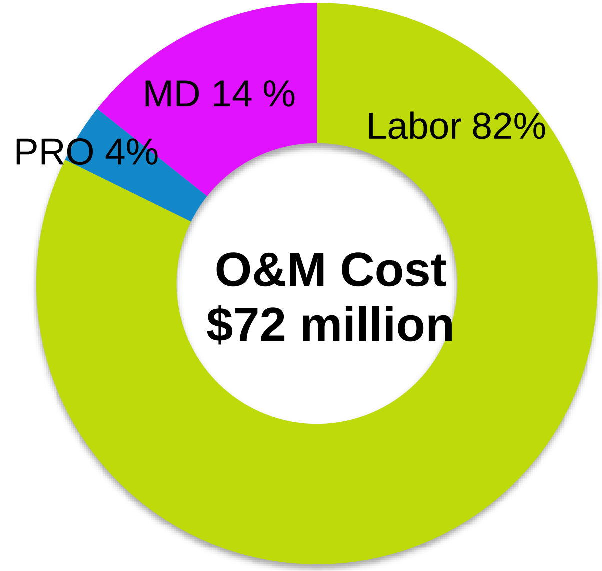
Equipment efficiencies	
Pump efficiency	70 %
Turbine efficiency	90 %
Pressure exchanger efficiency	95 %
Generator efficiency	95 %
Heat exchanger efficiency	60 %
Data and other assumptions	
Plant life	20 yr
Plant availability	90 %
PRO membrane replacement	10 %/yr
MD membrane replacement	10 %/yr
Interest (discount) rate, I	8 %
Inflation rate, n	3 %
Amortization factor	0.1
Labor cost	0.03 $/m^3
Specific membrane costs*	
PRO membrane element cost	11 $/m^2
MD membrane element cost	24 $/m^2
PRO membrane housing cost	17 $/m^2
MD membrane housing cost	14 $/m^2

**Assumed 35% mark-down from quoted distributor cost*

OHE Power Generation

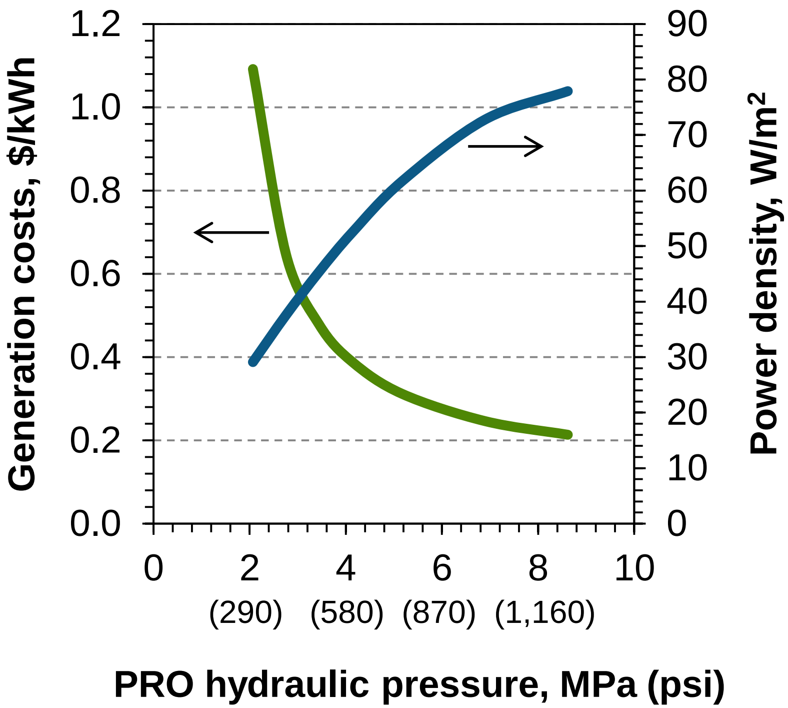
- Power outputs
  - Gross Power: 4.9 MW
  - Net Power: 2.5 MW
- About 20 % of capital costs due to bleeding
- Process efficiency
  - Theoretical efficiency[1] 4%
  - System efficiency 0.1%
- System costs: $0.48 per kWh
  - →Benchmark <$0.20 per kWh

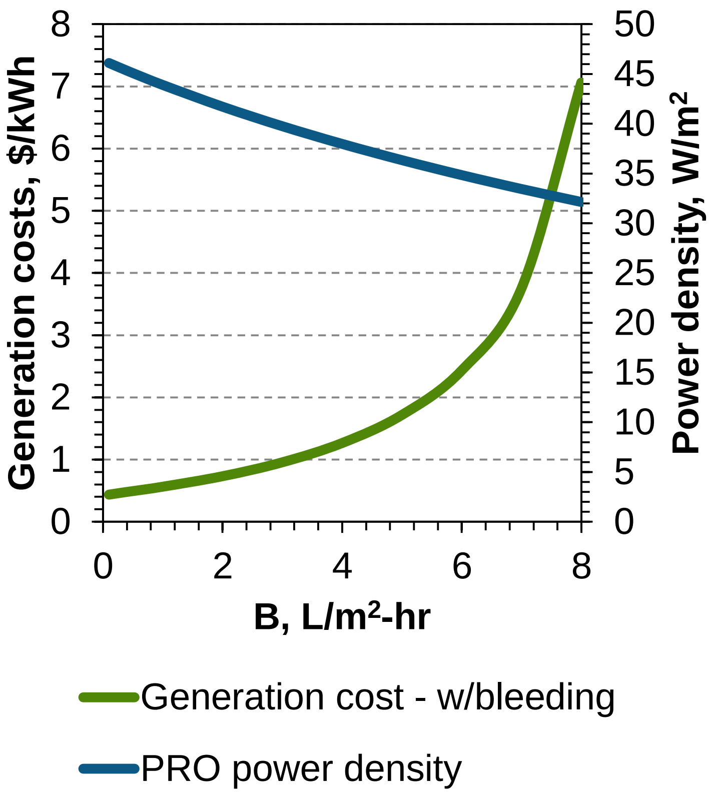




[1]*Lin et al., ES&T 2014*
Hickenbottom et. al, in Prep.

Cost Sensitivity:
PRO Power Density and solute permeability(B)





Assumptions and Model Outputs: Ideal Case OHE

- 25 MW (net power) system (economy of scale)
- Draw solution: 3 M NaCl
- PRO operating pressure: 7.6 MPa (1,100 psi), corresponding to a PRO power density of 76 W/m^2
- MD temperatures: 85 ° C feed, 15 ° C distillate

OHE Sensitivities

	Base	Ideal	Unit
System size (net power)	2.5	25	MW
Electricity generation cost	0.48	0.10	$/kWh
PRO operating pressures	4	7.6	MPa
PRO power density	45	76	W/m^2
PRO recoveries	15	40	%
MD feed (LGH) temperature	70	85 (95)	°C
MD distillate (cooling) temperature	30	15 (5)	°C
MD recoveries	6	30	%
MD water flux	27	38	L/m^2-h
Membrane replacement	10	5	%/yr

Costs of Competing Energy Generation Technologies

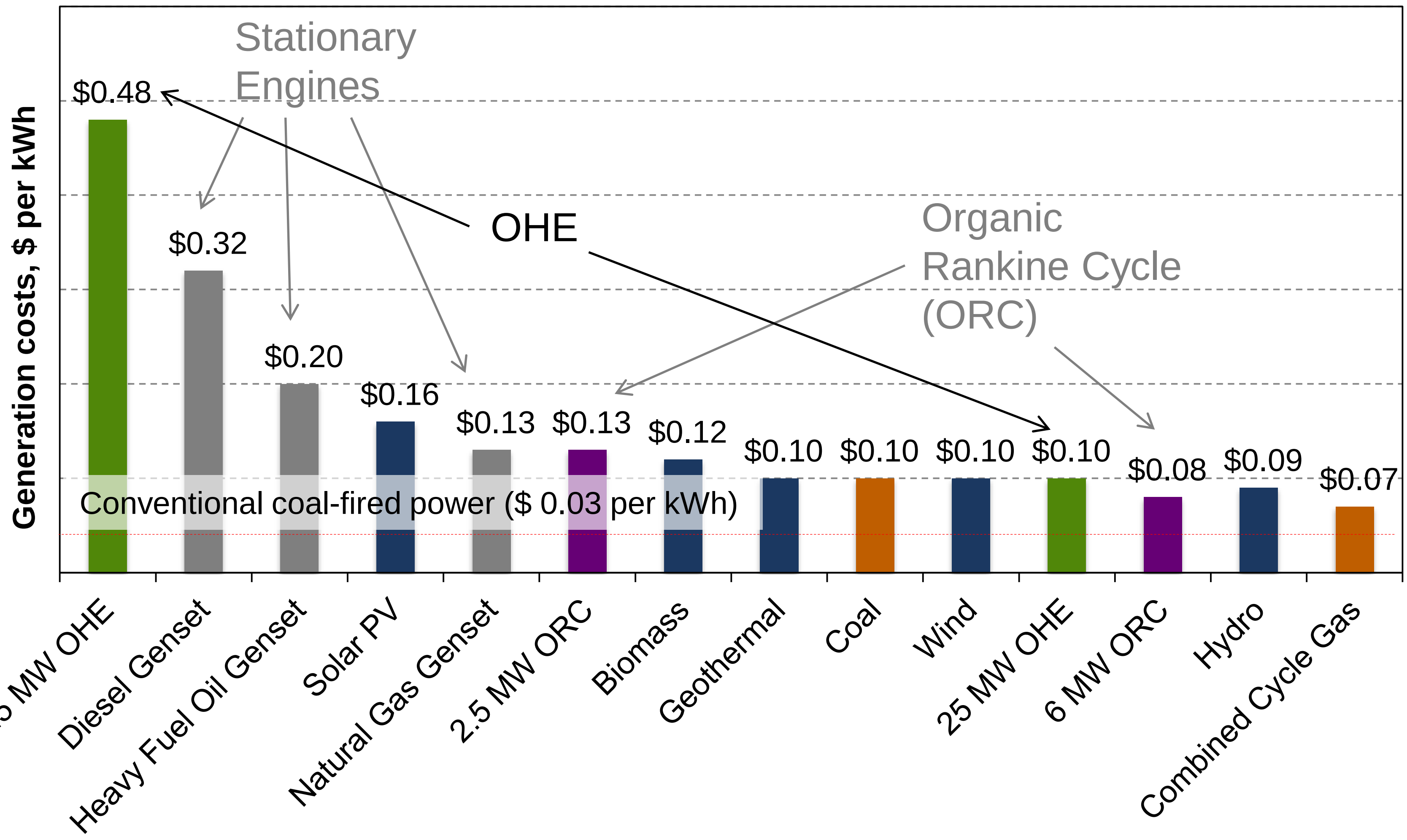
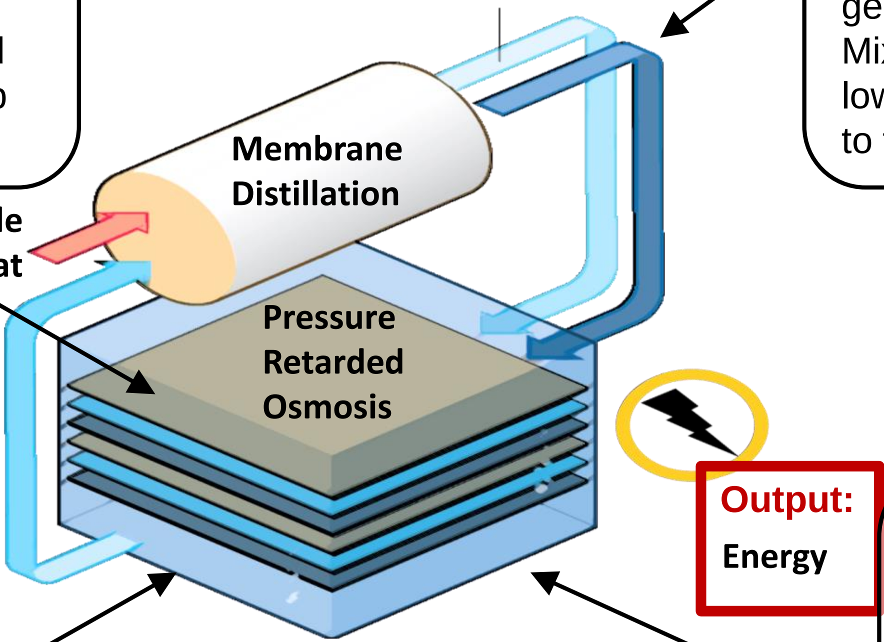


**Figure adapted from US EIA's Annual Energy Outlook 2012; and ElectraTherm 2013*

Conclusions

HTI TFC membranes are the best commercially available PRO membranes, withstanding operating pressures up to 500 psi and attaining power densities up to **22 W/m^2**

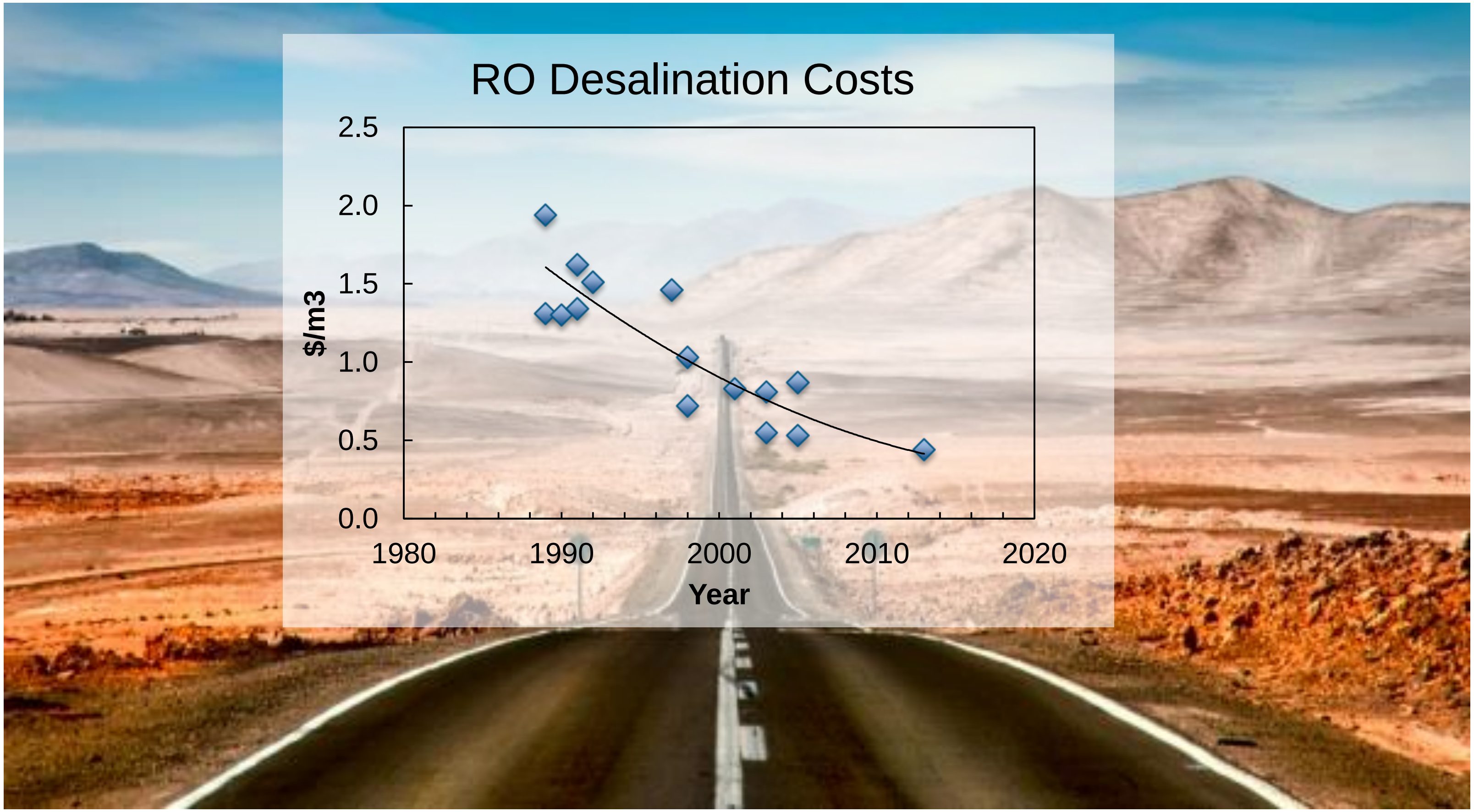
Use of $CaCl_2$ and $MgCl_2$ as working fluids, can decrease OHE electricity generation costs **by > 46%.** Mixed draw solutions with low RSF have the potential to further decrease costs.



Changing spacer orientation from parallel to 45° increased PRO power densities with **48 %**

Future improvements to PRO membranes and power densities **(> 76 W/m^2)** could make the OHE a competitive renewable energy and energy storage technology.

The future of osmotic power and the OHE?



Greenlee et al., Water Ressarce 43 (2009) 2317– 2348.

Acknowledgements

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Thank you!