Development of Membrane Distillation Technology Utilizing Waste Heat for Treatment of High Salinity Wastewaters

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Outline

- Introduction on Membrane Distillation
- Laboratory Experiments and Results
- Waste Heat Availability
- Systems Level Analysis
- Conclusions

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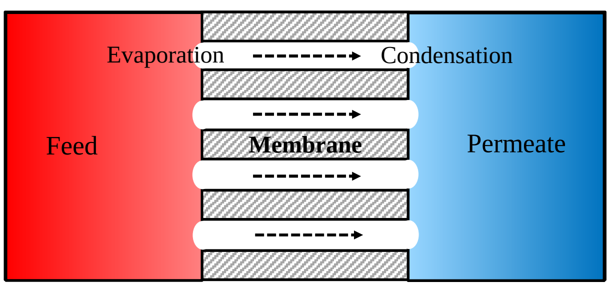
Treatment and Disposal Strategies

- Deep well injection
  - Linked with seismic activities
  - Viable as long as Class II injection wells are available
- Reverse Osmosis
  - Not feasible for wastewater with TDS> 40,000 mg/l
- Evaporation/Crystallization
  - Above 90% water recovery
  - High energy intensity and cost
- Recycling water for subsequent fracking
  - TDS interferences with hydraulic fracturing chemicals (e.g., friction reducers)
  - Water hardness is an issue
  - Bacteria is a concern
  - Barium can form sulfates and hence create scale

Direct Contact Membrane Distillation (DCMD)



Schematic diagram of liquid/vapor interface across a hydrophobic membrane

- Vapor pressure driven process
- Hydrophobic membranes
- Pore size – 0.2 to 1 µm
- Membranes material – PTFE, PVDF, PP, AC
- Permeate flux is proportional to vapor pressure difference

- Advantages
  - Operates at low temperature (<100°C)
  - Low quality heat energy can be used
  - Ambient pressures
  - Not highly affected by salinity
  - Produces high quality water
- Disadvantages
  - Conduction heat losses
  - Energy consumption (upto 3.5 MWh/m^3)[1]

[1] A. Criscuoli, M.C. Carnevale, E. Drioli, Evaluation of energy requirements in membrane distillation, Chemical Engineering and Processing: Process Intensification, 47 (2008) 1098-1105

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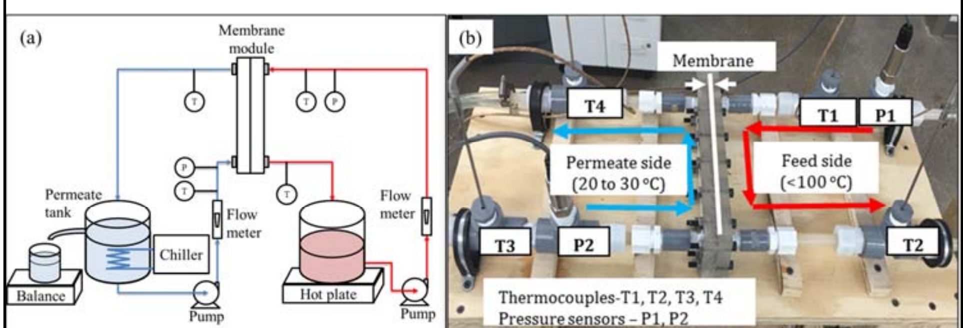
Experimental Setup



(a) Schematic diagram of experimental setup, (b) Picture of the DCMD module

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Membranes Properties

Membrane	Mean pore radius (µm)	Thickness (µm)		Contact angle (active layer)	Membrane Porosity (%)		Thermal Conductivity (W/m.K)
		Total	Active layer		Bulk	Active Layer	
AC	0.23	215	-	135	30	-	0.105
PP	0.38	135	-	136	79	-	-
PTFE 1	0.21	112	20	142	42	92	0.294
PTFE 2	0.25	210	22	147	37	-	-
PTFE 3	0.24	148	60	149	60	94	0.242
PVDF	0.19	145	-	107	68	-	-

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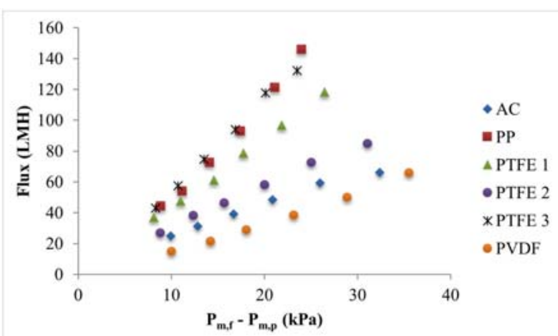
Performance of different membranes



Flux (LMH) vs Vapor pressure difference (kPa)

Membrane	MD coefficient (LMH/kPa)
AC	2.2
PP	5.6
PTFE 1	4.4
PTFE 2	2.8
PTFE 3	5.6
PVDF	1.7

Operating conditions:

- Feed and permeate velocity= 0.6 m/s
- Feed - pure water
- Permeate temperature=30°C

Flux unit – LMH (l/m^2/hr)

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Produced water characterization

Component (mg/l)	Site 1	Site 2
Cl^-	188,728	63,588
Na^+	81,442	26,427
NH_4^+	1,002	279
K^+	786	258
Mg^{+2}	2,664	675
Ca^{+2}	32,901	6,523
Sr^{+2}	11,910	1,620
Ba^{+2}	6,256	3,743
Fe total	30	10
TDS	308,334	92,800
TOC	0	11
*Ra226	17,980 ± 1,100	753 ± 60

* Ra 226 activity is shown in pCi/l

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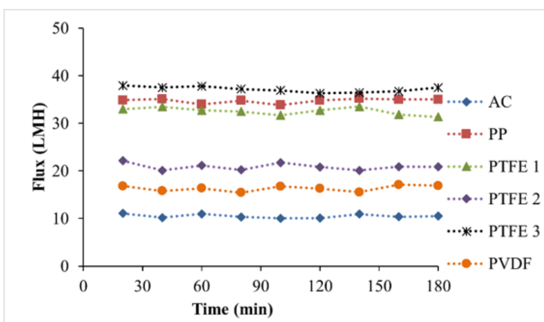
Constant concentration - Site 1



- Constant flux over time
- Negligible scaling even at a high TDS

- Constant concentration
- TDS = 308,334 mg/l
- Feed temperature = 60 °C
- Permeate temperature = 30°C
- Feed and permeate velocity=0.6 m/s

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Permeate Quality

Membrane	Cl^- (ppm)	Rejection %	Average Flux (LMH)
AC	2	99.9	10.5
PP	7	99.9	34.7
PTFE 1	0.5	99.9	32.5
PTFE 2	1	99.9	20.8
PTFE 3	2	99.9	37.5
PVDF	1	99.9	16.3

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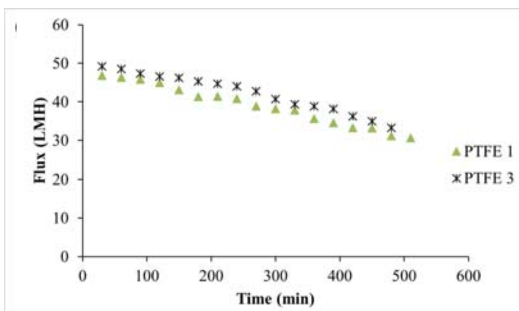
Concentrating produced water – Site 2



- Feed was concentrated until TDS reached 30%
- Pure water flux with the used membranes was equal to that with pristine membranes
- Permeate quality:

	PTFE 1	PTFE 3
Cl- (mg/l)	0.4 (99.9% rejection)	0.5 (99.9% rejection)
Ra 226 (pCi/l)	ND	ND
TOC (mg/l)	1 (90.9% rejection)	0.83 (92.4 % rejection)

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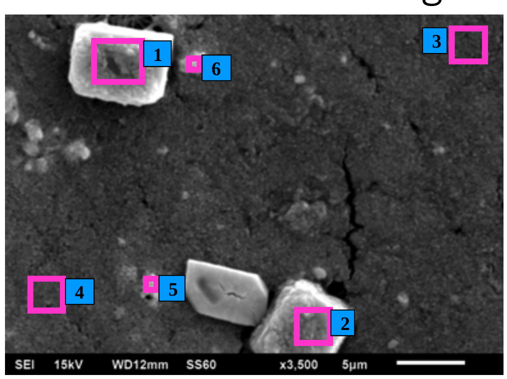
- Pristine membrane

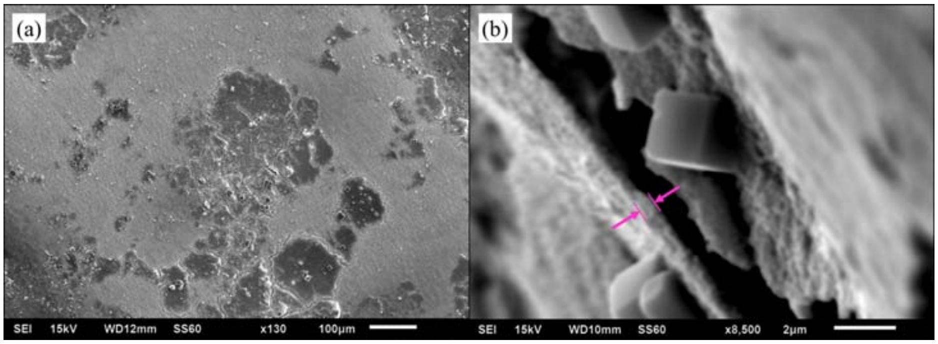
- Used membrane

Membrane Fouling



Location	Weight %							
	O	Na	Mg	Cl	Ca	Fe	Sr	Ba
1	11	31	0	51	1	5	0	1
2	9	31	0	56	1	3	0	0
3	43	0	1	10	6	37	0	2
4	44	1	1	10	6	37	0	2
5	32	2	0	5	2	11	2	46
6	30	2	0	8	4	22	1	34

- Iron fouling may be a problem in the long run
- Pretreatment should be considered



- Scaling is not uniform on membrane surface
- Scale thickness is of the order of a few microns

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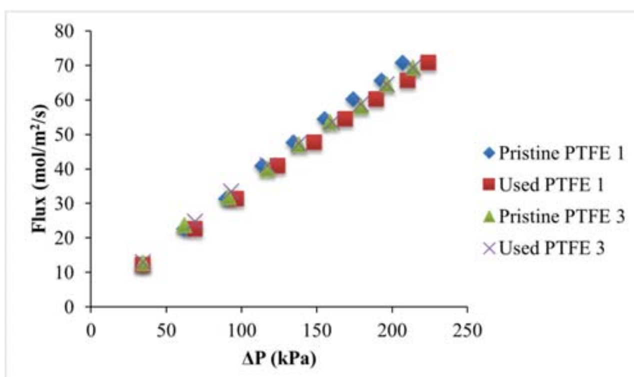
Gas Permeation Tests



- Pristine and used membranes almost identical

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Experimental Results

- Membrane pore radius and porosity significantly affect MD coefficient
- Membrane support thickness and porosity influence the permeate flux
- Direct Contact Membrane Distillation can be used to concentrate produced water
  - Stable operation of produced water treatment with negligible scaling
  - PTFE membrane with polypropylene support is most promising

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Systems Level Analysis

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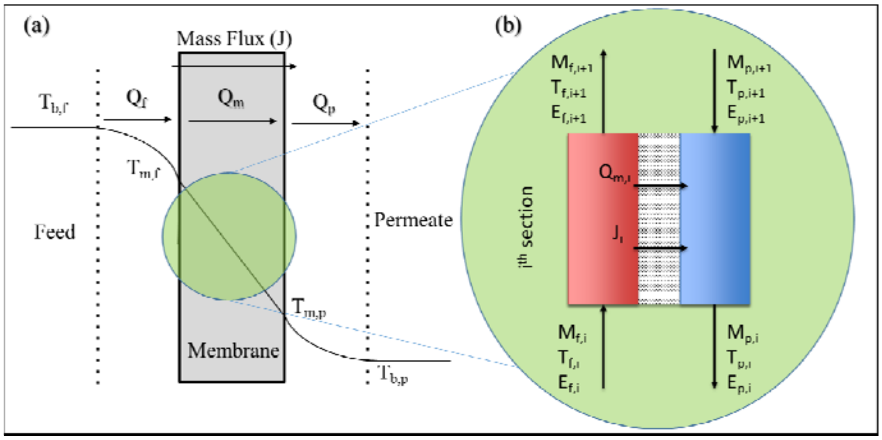
Stepwise Modelling



(a) Temperature profile across the membrane (b) Small section of the membrane

- Divide membrane into 'n' parts
- Solve for each part sequentially

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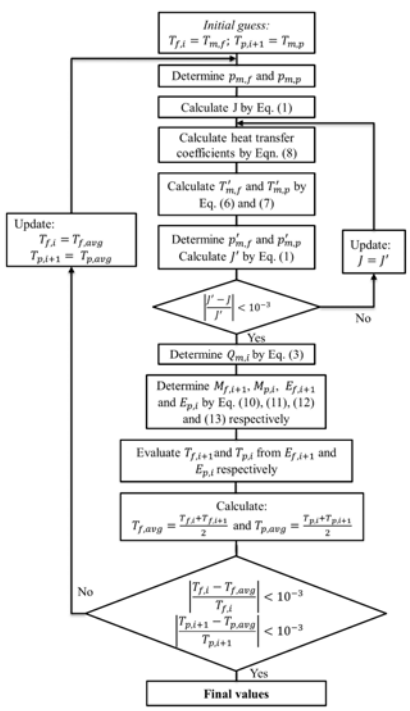

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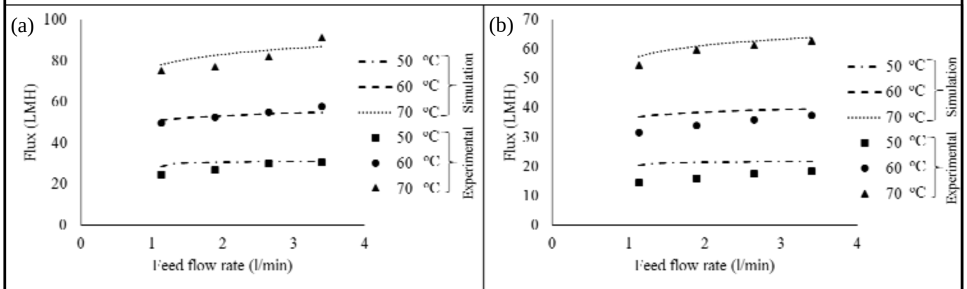
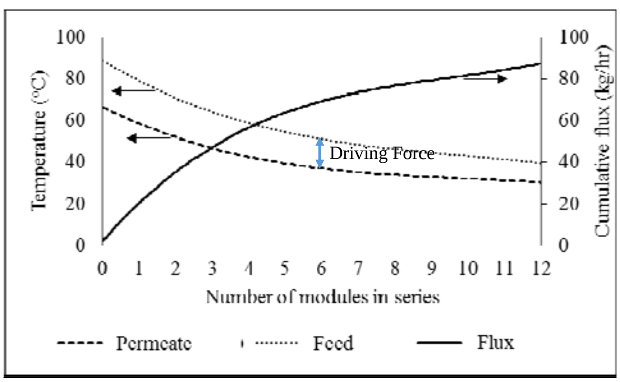
Model Calibration and Validation



Flux vs flow rate at 50, 60 and 70 °C for (a) 93 g/l and (b) 308 g/l TDS produced water solutions

- Model was calibrated at 60 °C and 1.9 l/min

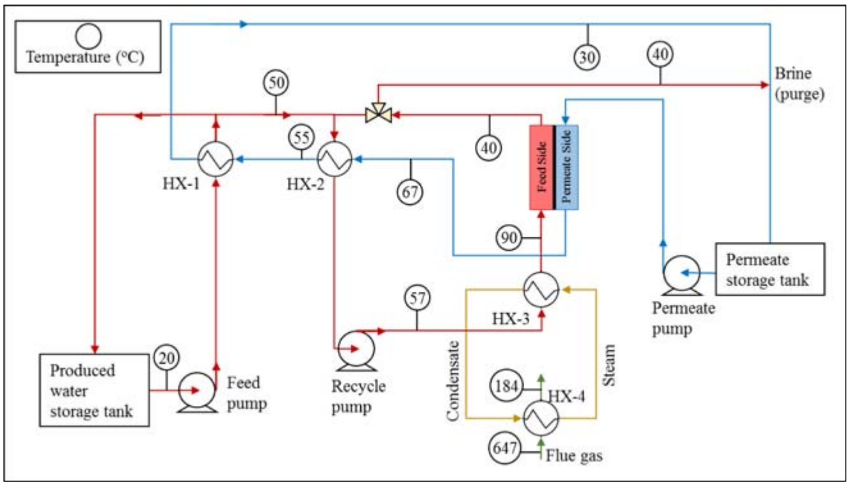
Simulation Results



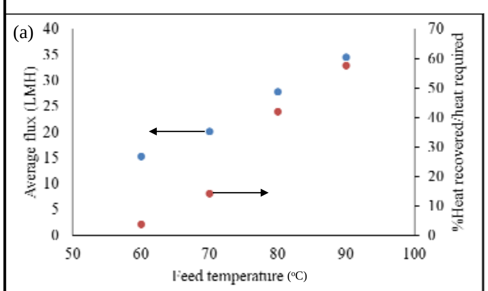
Temperature and flux profiles for 12 modules in series

- Assuming 1 module has an area of 0.2 m^2
- Minimum temperature difference of 10 °C was selected
- 12 modules in series

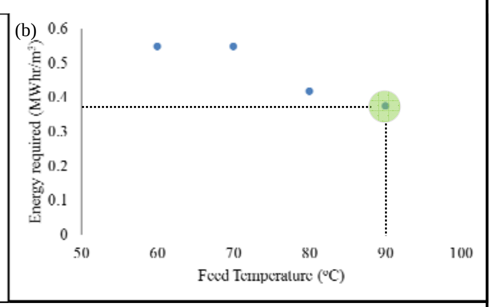
Systems Level Flow-sheet



Process flow-sheet for water treatment using waste heat



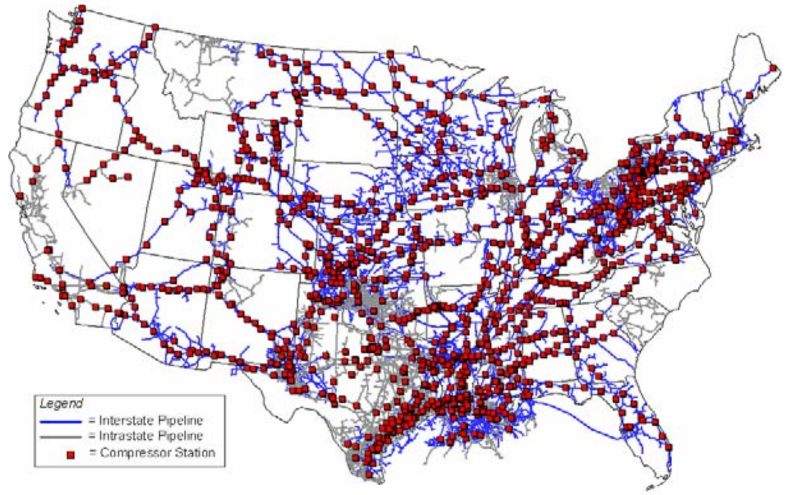
(a) Average flux and percent heat recovery vs Feed Temperature



(b) Energy required per m^3 of produced water vs Feed Temperature

- Raising the feed temperature increases flux and heat recovery
- More energy is required at lower feed temperature

Natural Gas Compressor Stations



Source:US Energy Information Administration

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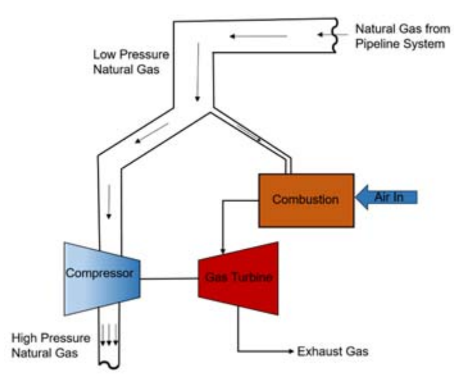
Waste Heat Estimation



- Waste heat from natural gas compressor stations estimated to be 46 TJ/day in PA.

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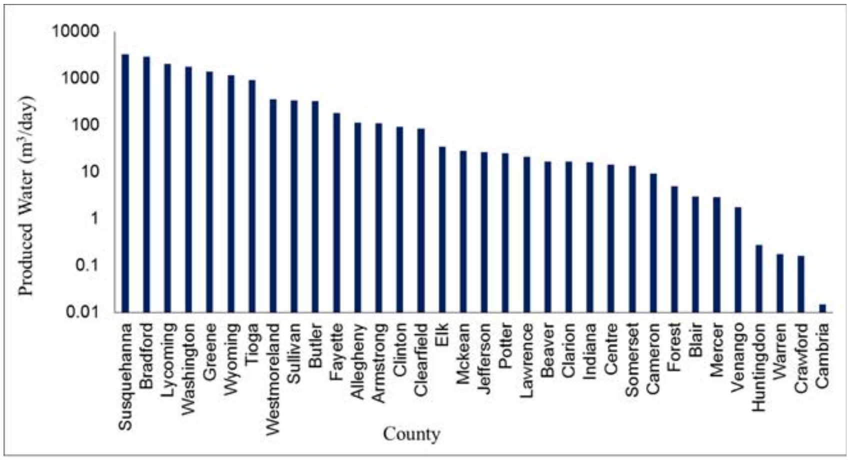
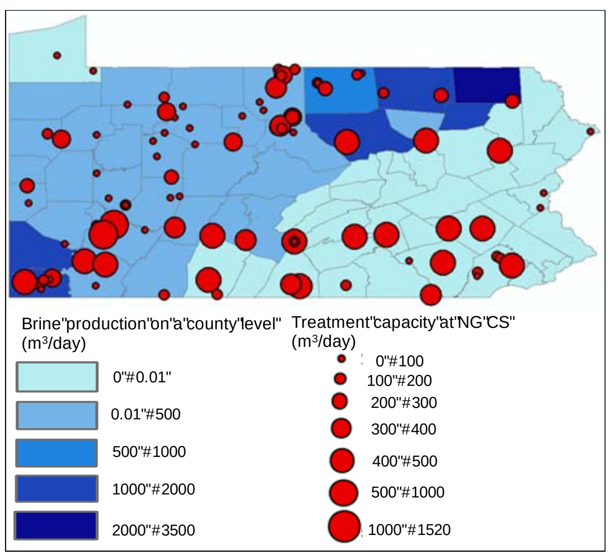
Quantification of Produced Water in PA



- Total of about 2.7 million m^3 produced in six months (2014)

How much produced water can be treated?

- 54% of waste heat from NGCS is required to concentrate produced water in PA to 30% salinity
- Practical constraints
  - Water transportation
  - NGCS load factor



Summary

- DCMD can be used to concentrate produced water
    - Stable operation of produced water treatment with negligible scaling
- Developed an ASPEN simulation to estimate flux and temperature profiles for a scaled up DCMD process
- Quantified waste heat available from NGCS in PA
- 54% of waste heat from NGCS is required to concentrate produced water in PA

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