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

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2017 Crosscutting Research Portfolio Review
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Outline

- Objectives
- Milestones
- Objectives (in detail)
  - Approach
  - Results
- Conclusions

Objectives

1. Evaluation of DCMD for treatment of high salinity water VRD1
   - Laboratory testing
2. Modelling DCMD in ASPEN
3. Waste heat estimation
4. Systems Level Analysis
   - DCMD integration with waste heat
   - Techno-economic analysis

Slide 3

VRD1 Need to mention here both produced water and water from CO2 sequestration
Vidic, Radisav D, 3/21/2017

Milestones

- Research papers
  - Systems-Level Analysis of Waste Heat Recovery Opportunities from Natural Gas Compressor Stations in the US, *ACS Sustainable Chemistry & Engineering* (2016), 4(7), 3618-3626.
  - Fouling in direct contact membrane distillation of produced water from unconventional gas extraction, *Journal of Membrane Science* (2017), 524, 493-501.
  - Integrating Membrane Distillation with Waste Heat from Natural Gas Compressor Stations for Produced Water Treatment in Pennsylvania, *Desalination* (2017), 413, 144-153.
  - A techno-economic assessment of membrane distillation for treatment of Marcellus shale produced water, *Desalination* (under review)

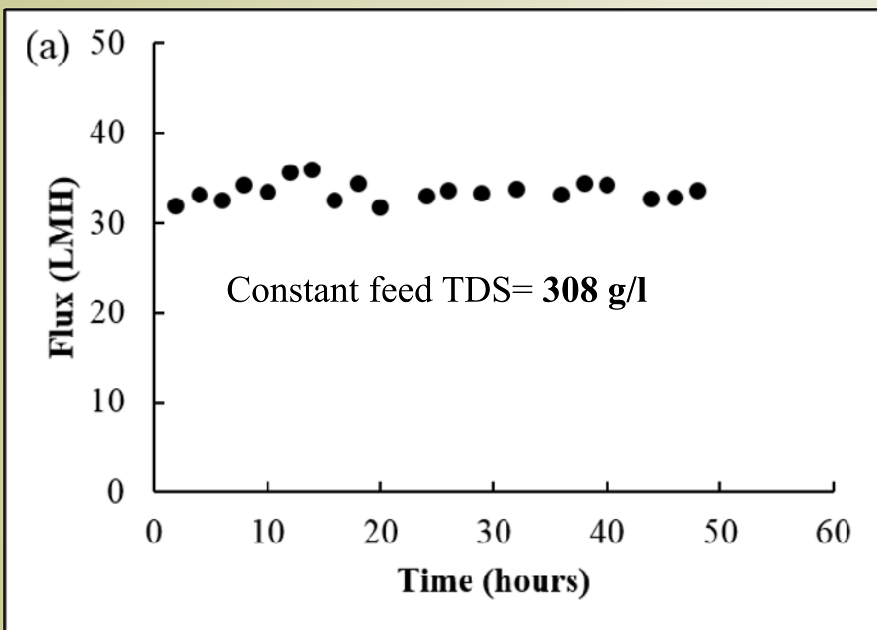
- Conferences Presentations
  - 251st American Chemical Society National Meeting & Exposition, 2016
  - Membrane Technology Conference & Exposition, 2017
  - American Institute of Chemical Engineers, 2016
  - Advanced Membrane Technology VII, 2016
  - International Society for Industrial Ecology (ISIE), 2015
  - American Institute of Chemical Engineers (AIChE) Annual Meeting, 2015
  - Desaltech, 2015

1. Evaluation of DCMD for produced water treatment

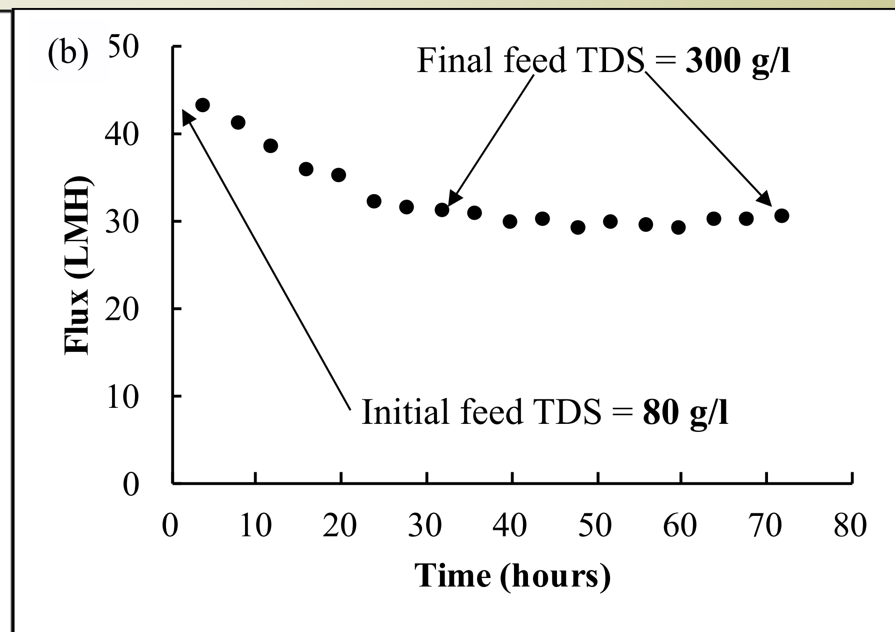
- Fouling studies with actual produced water
  - Identify possible foulants
  - Total Fe from 10 to 91 mg/l
- Long term experiments
  - Up to 3 days of operation
- Impact of salinity
  - TDS 92,800 to 308,000 mg/l

Results

Constant Concentration Mode



Continuous Mode

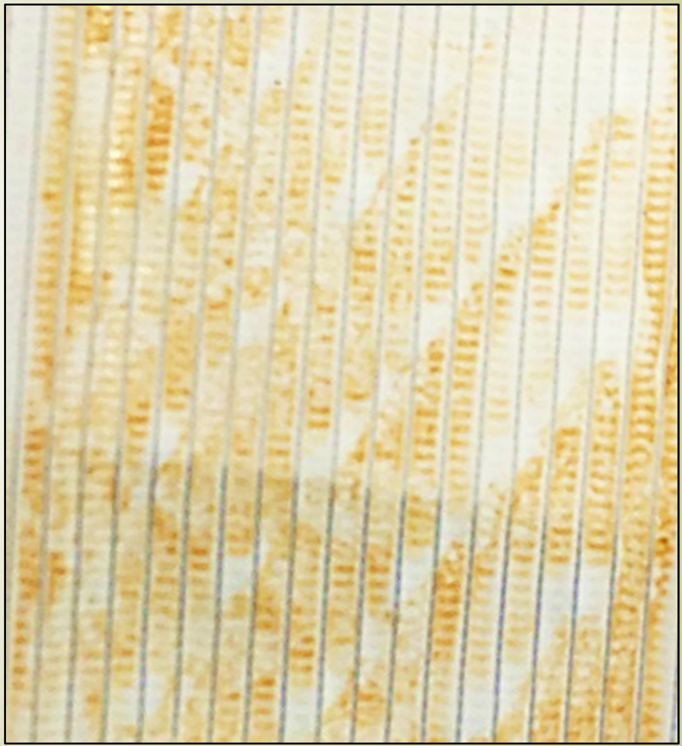


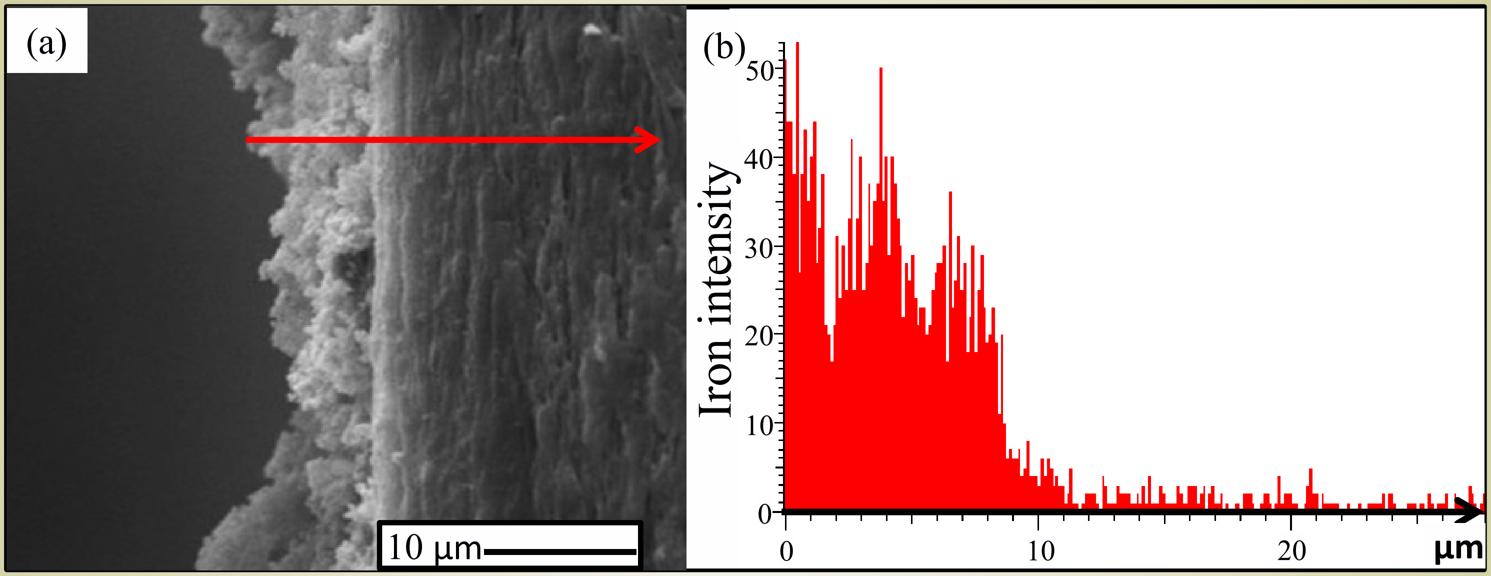
- No obvious flux decline due to fouling
- 99.9% of salt rejection

Lokare, O. R.; Tavakkoli, S.; Wadekar, S.; Khanna, V.; Vidic, R. D., *Journal of Membrane Science* **2017,** *524*, 493-501.

- Pristine membrane

- Used membrane





(a) SEM image showing the membrane cross section and

(b) EDS line scan to evaluate the thickness of the scale layer

- Iron fouling with a thickness up to 12 µm

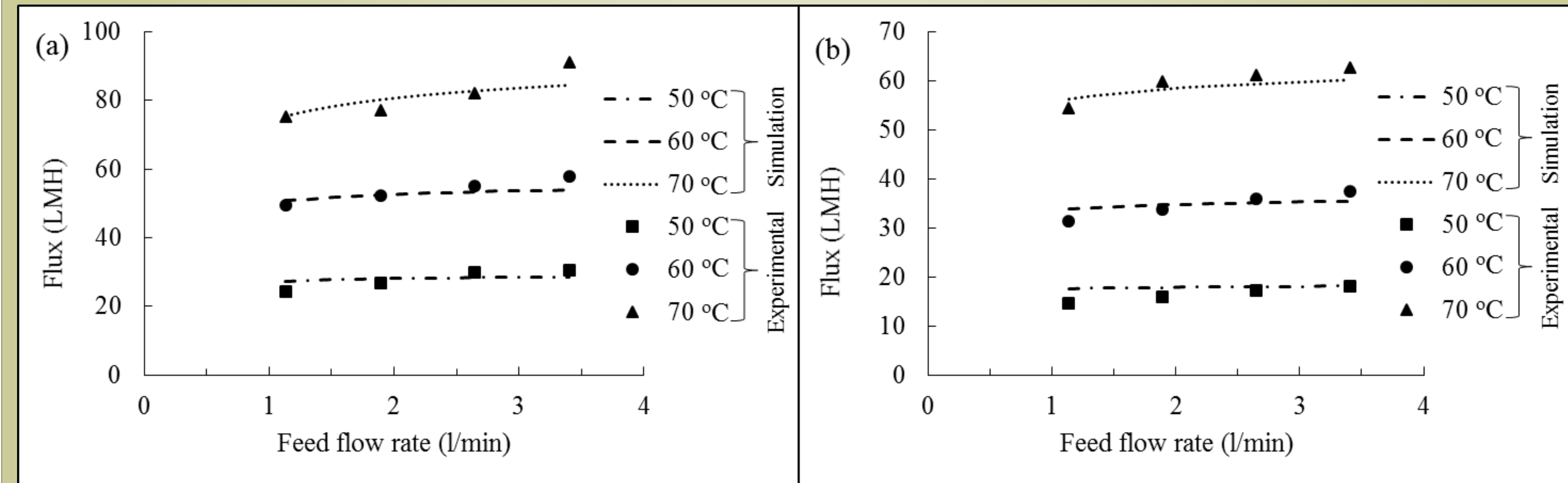
Lokare, O. R.; Tavakkoli, S.; Wadekar, S.; Khanna, V.; Vidic, R. D., *Journal of Membrane Science* **2017,** *524*, 493-501.

- Direct Contact Membrane Distillation can be used to concentrate produced water
  - Stable operation of produced water treatment with negligible scaling
- Iron is likely to foul membranes during produced water treatment
- Iron fouling has negligible effect on membrane performance
  - Porous nature of the foulant

2. Modelling DCMD

- Modelled DCMD using a stepwise modelling approach
- Incorporated the model in an ASPEN Plus platform
- Calibrated the model for high salinity solutions

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 actual produced water

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

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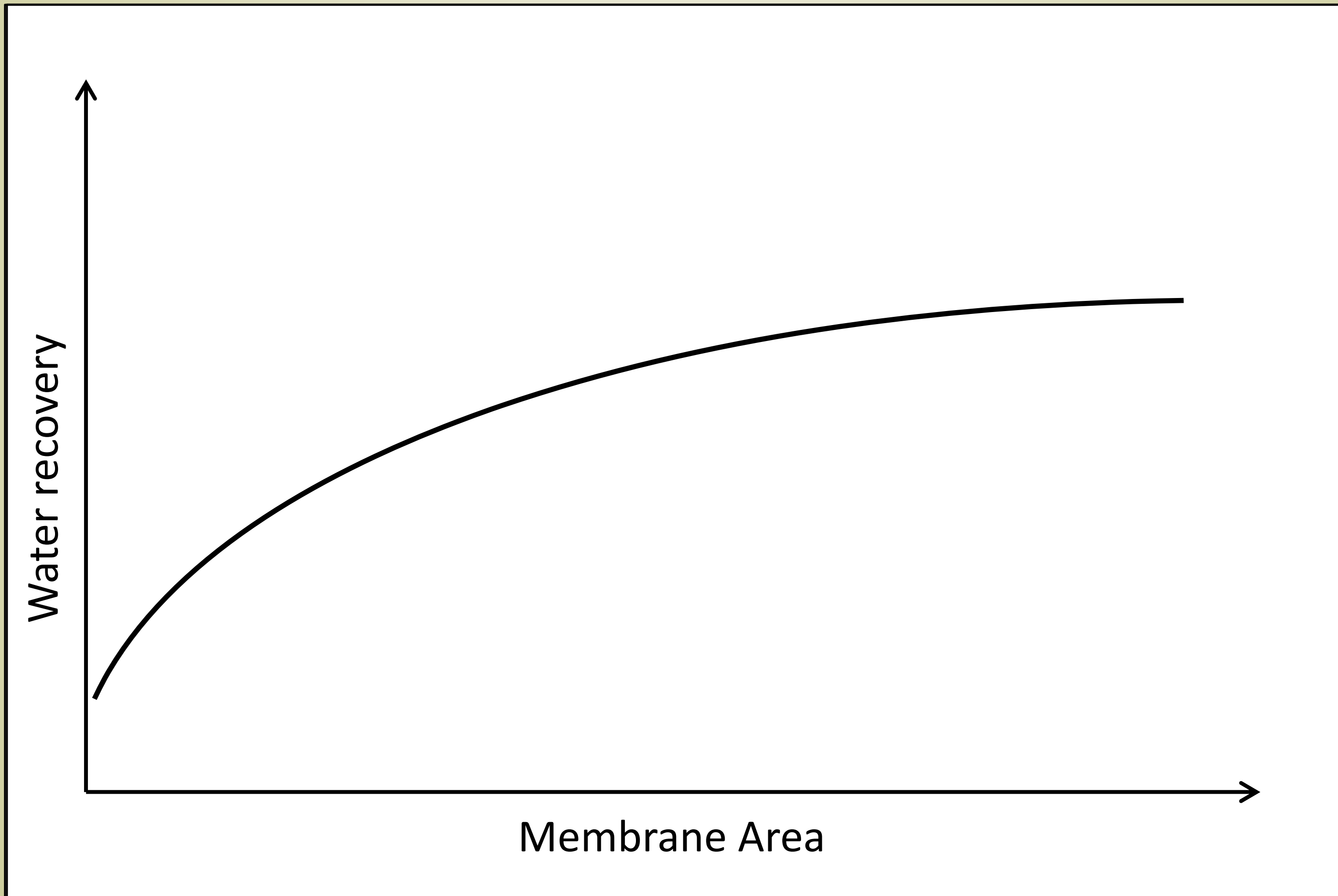
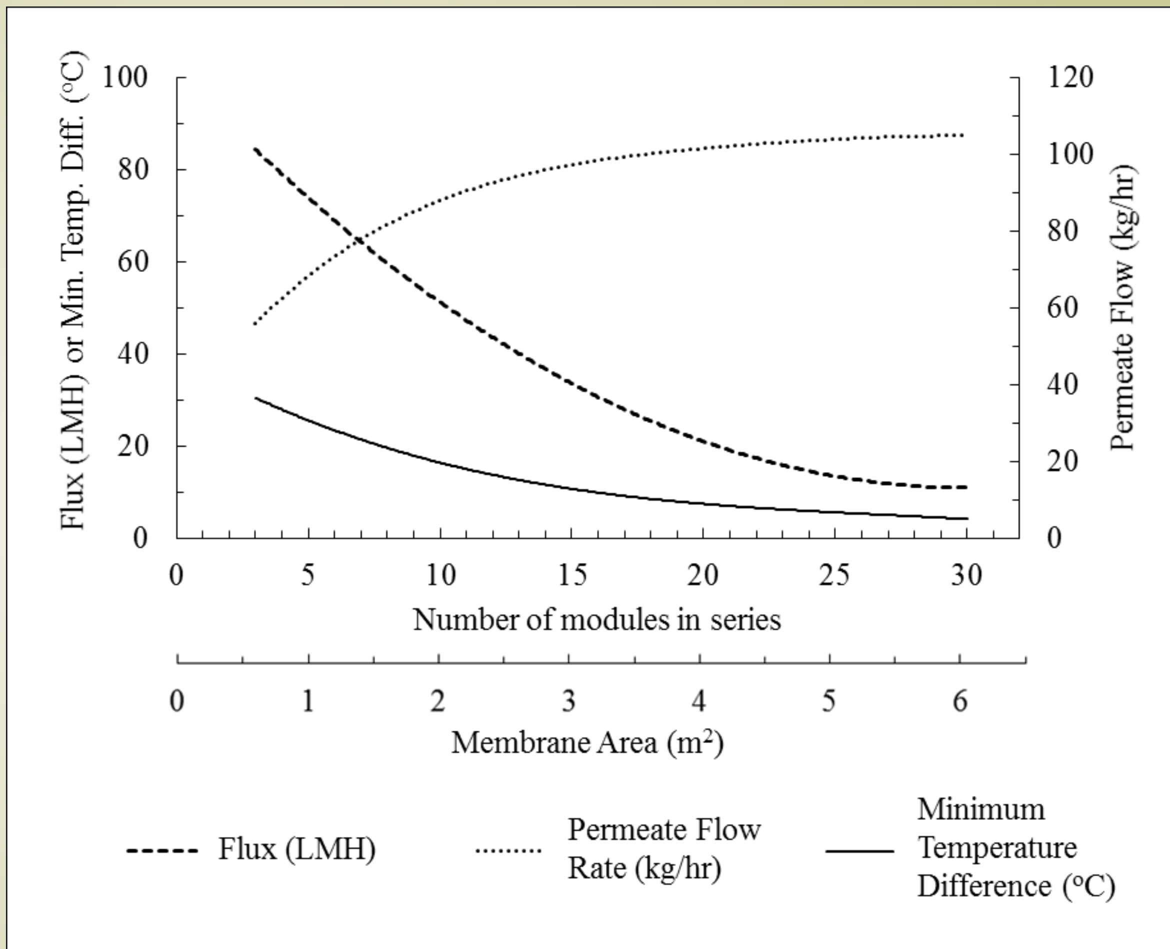
Temperature and flux profiles in DCMD



Simulation Results

- 1 module is assumed to have an area of 0.2 m^2
- Permeate recovery eventually becomes constant
- Hence, minimum temperature difference of 10 ^{o}C was selected



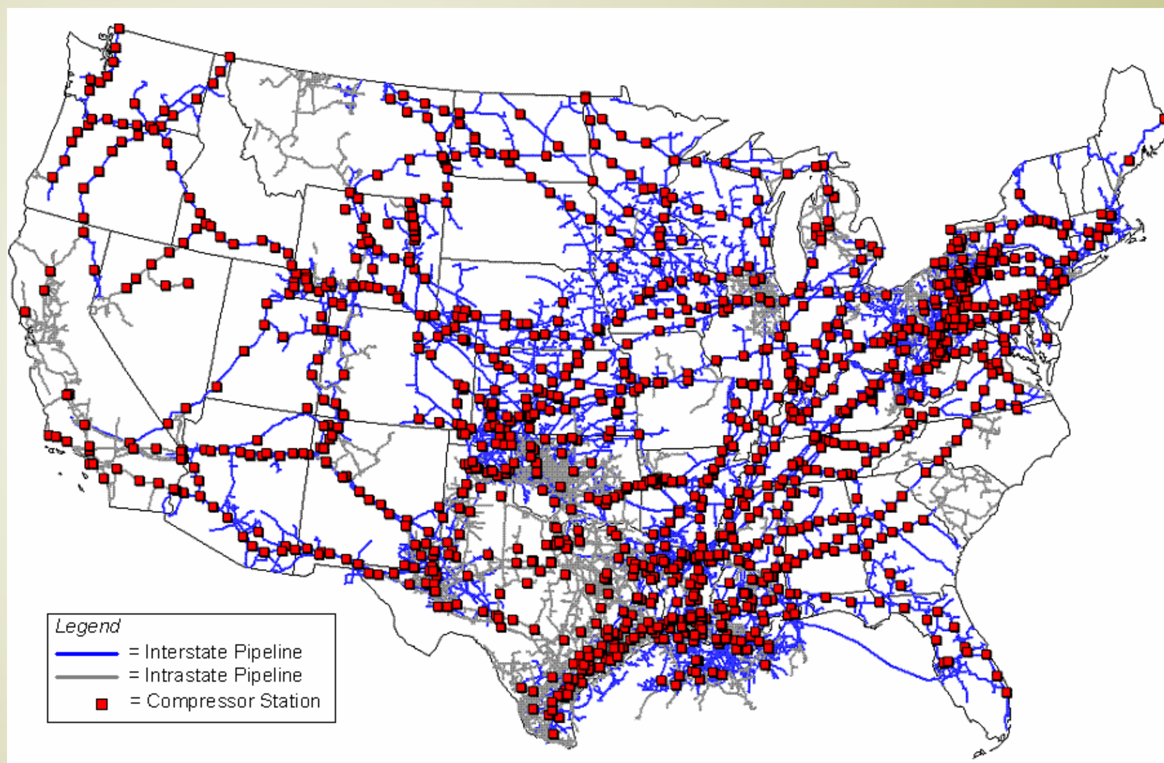
Lokare, O. R.; Tavakkoli, S.; Rodriguez, G.; Khanna, V.; Vidic, R. D., *Desalination*, **2017**, 413, 144-153.

3. Waste heat estimation

- Identify a source of waste heat
  - Solar energy
  - Waste heat at power plants
  - Natural Gas Compressor Stations (NGCS)
- Estimate the amount of waste heat generated
  - Thermodynamic calculations

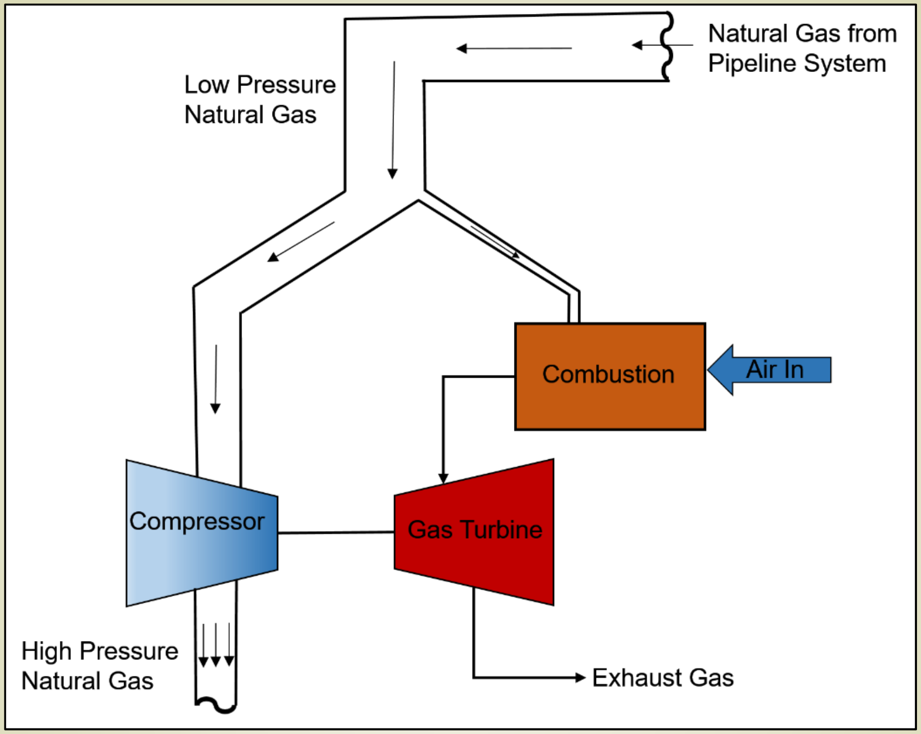
Waste Heat Source

- About 1,800 natural gas compressor stations
- Over 17 million installed horsepower
- There are 118 compressor stations in PA, 26 in OH, and 45 in WV



Source: US Energy Information Administration

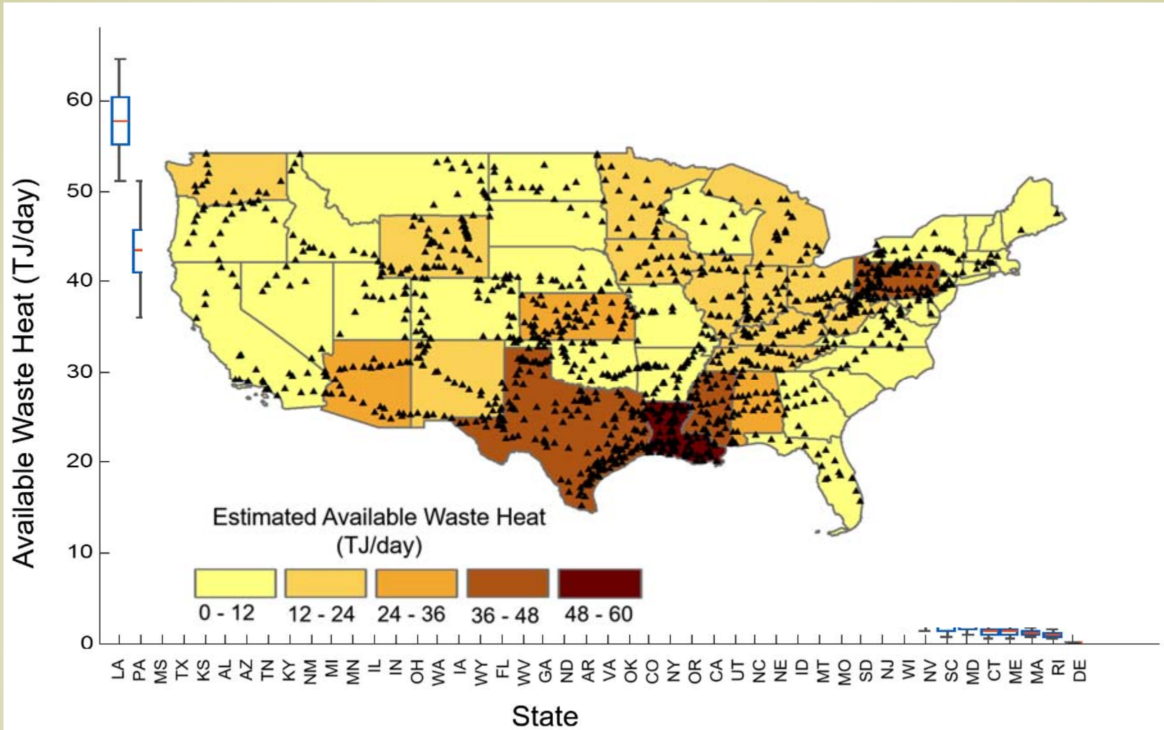
Thermodynamic Calculations



- Exhaust gas is estimated to be at a temperature of
  - 921 K for gas turbine compressor engines
  - 645 K for internal combustion engines

Tavakkoli, S.; Lokare, O. R.; Vidic, R. D.; Khanna, V., *ACS Sustainable Chemistry & Engineering* **2016,** *4* (7), 3618-3626.

Available Waste Heat at Compressor Stations



- 610 TJ/day of waste heat is available in the US from Natural Gas Compressor Stations[1]
- Pennsylvania alone generates about 43.4 TJ/day of waste heat

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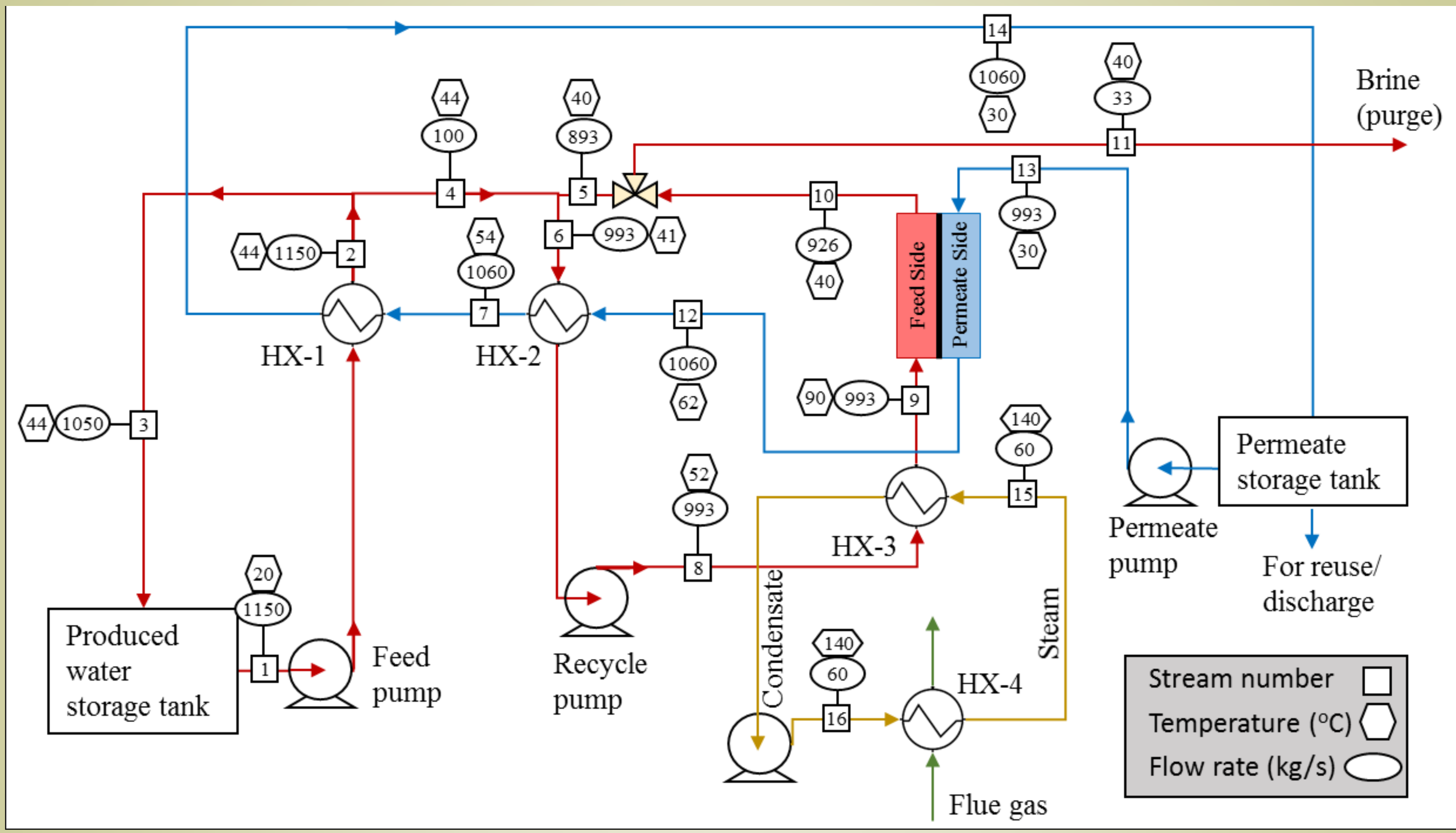
4. Systems Level Analysis:
DCMD integration with waste heat

Process Flow-Sheet



- Employed a heat recovery section

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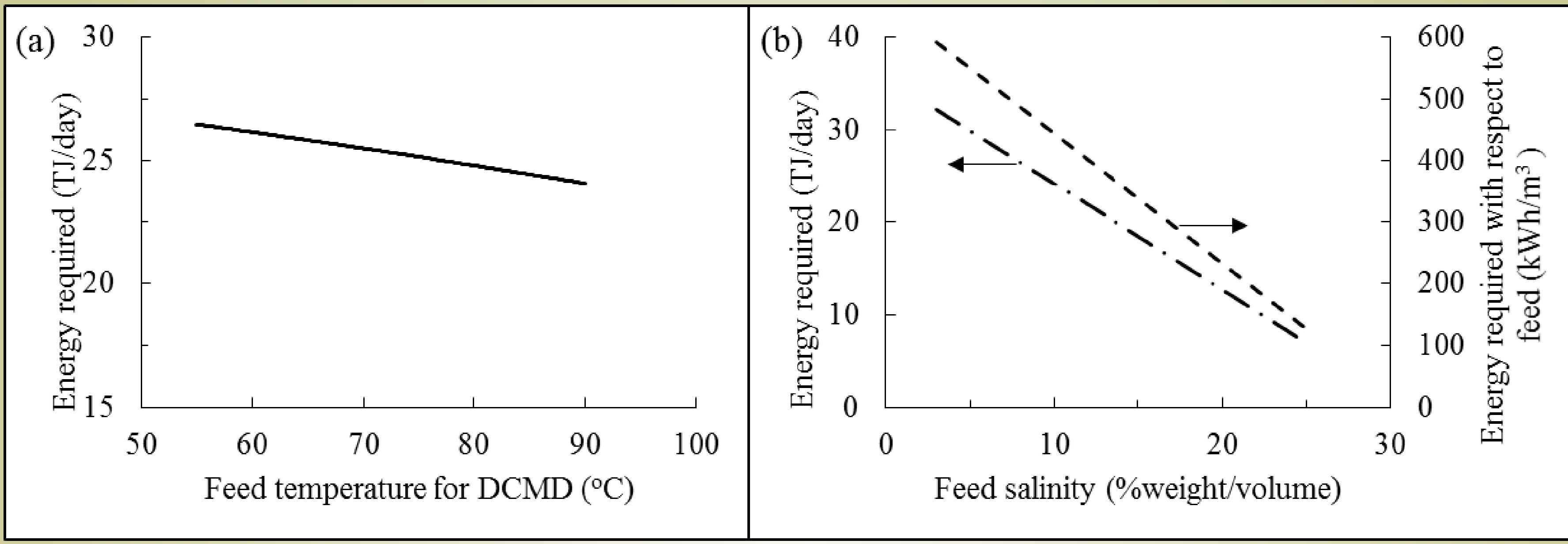

- Energy requirements for produced water treatment are much lower than the available waste heat from NGCS
- Effect of salinity doesn't affect this result

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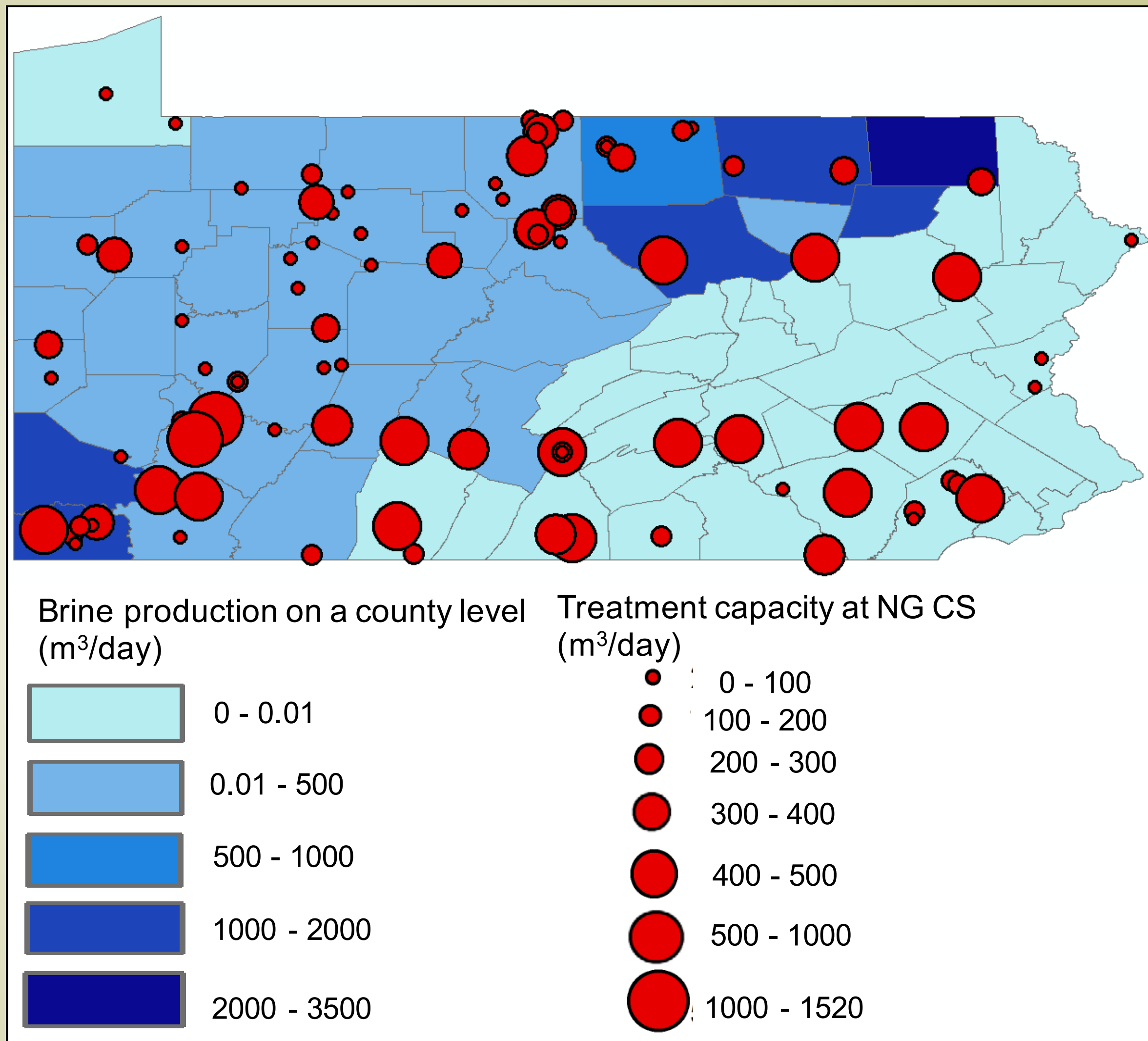
- 56% of waste heat from NGCS is required to concentrate produced water in PA to 30% salinity

- Practical constraints
  - Water transportation



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Results

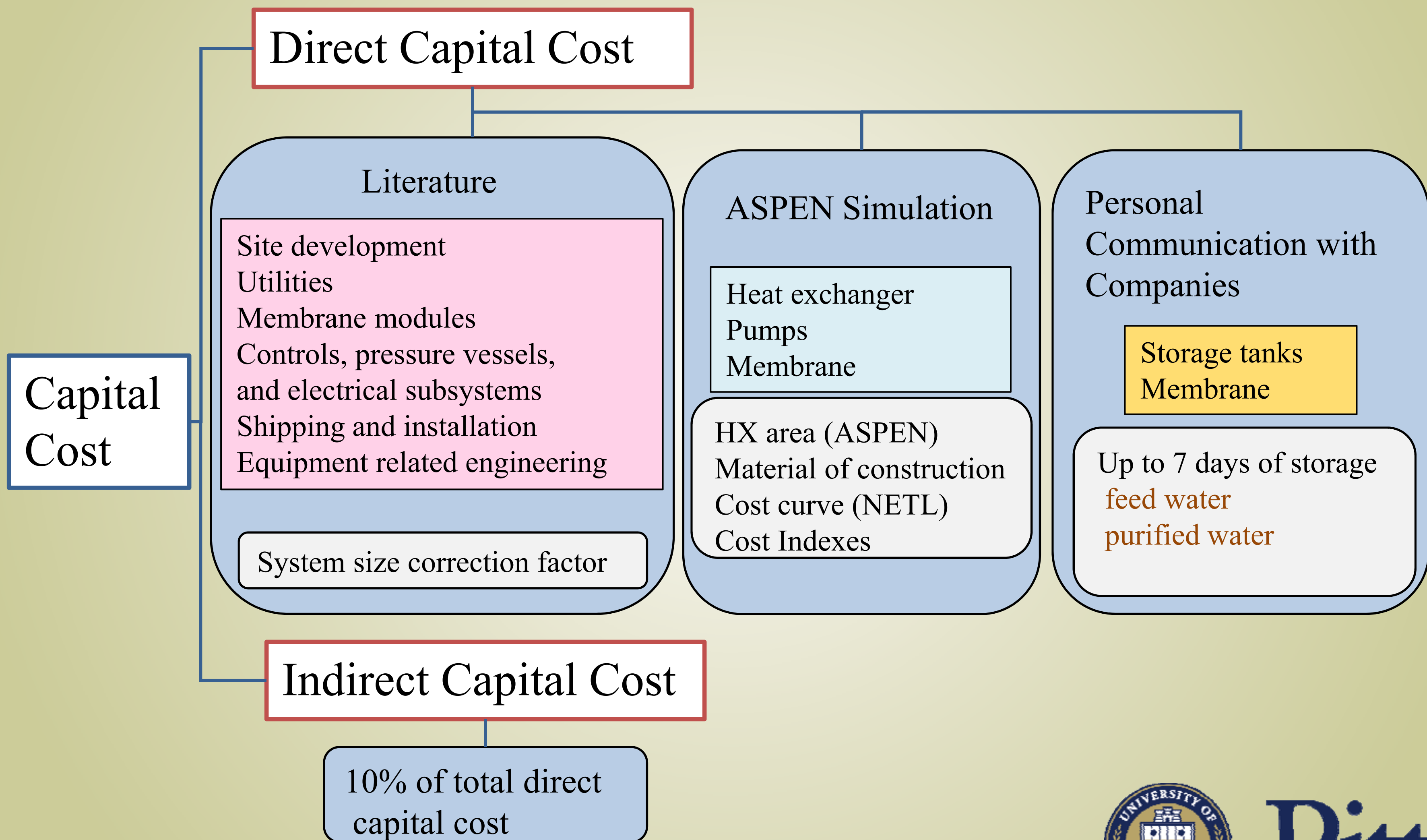
- Theoretically, only 56% of waste heat available in PA is required to treat all the produced water in PA
- Transportation of produced water to the waste heat source is likely to determine the economics

4. Systems Level Analysis:
Techno-Economic Analysis (TEA)

TEA Model

- Based on
  - Available literature
  - ASPEN simulation
- Hypothetical 0.5 million gallons per day DCMD plant
- Concentrating produced water from 100,000 to 300,000 mg/l
  - Recovery factor of 66.7 %
- Total cost
  - Capital cost
  - Operating and Maintenance cost (O&M)

Capital Cost



O&M Cost

O&M Cost

Energy

Thermal energy

- Main energy requirement
- ASPEN Plus
- Most recent thermal energy price

Electricity

- Four centrifugal pumps
  - Feed pump
  - Recycle pump
  - Permeate pump
  - Condensate pump
- Electricity price (US EIA) for base year 2015

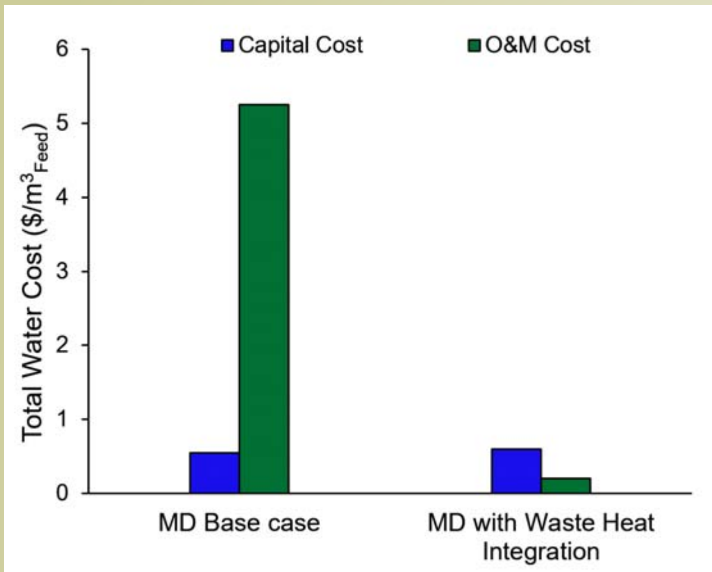
Intake

- Capital cost for seawater desalination (e.g., surface open intake, beach well)
- Operating cost in the case of produced water treatment
- Function of transportation distance as well as volume of produced water
- Truck transportation

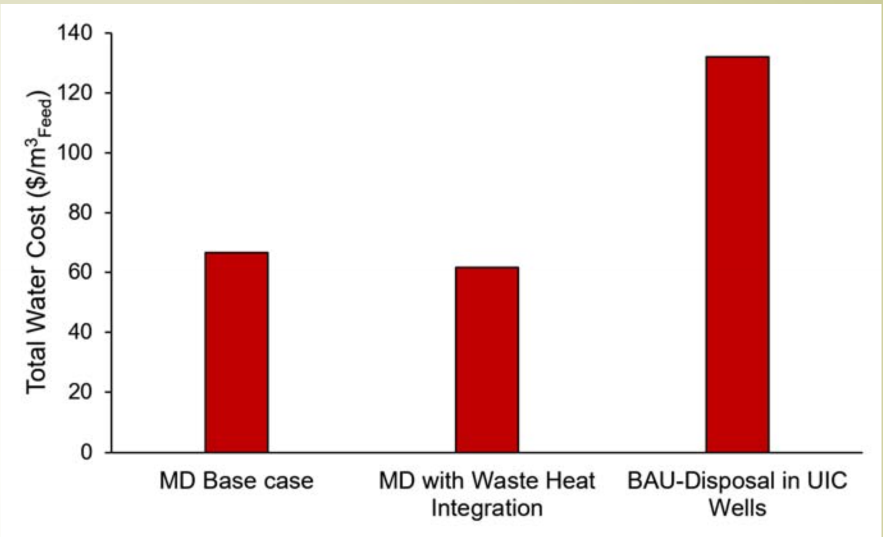
Other

- Filter
- Brine disposal
- Chemicals
- Spare
- Membrane replacement
- Labor

Results: Produced water Treatment vs Disposal



a) Capital and O&M costs (dollar per cubic meter of feed water)



b) Treatment vs disposal comparison

Increased capital cost when integrated with waste heat

- Additional cost for heat recovery system
- $394,000 higher for the plant with waste heat integration

Reduced O&M costs

- Total saving of $3.13 million per year in O&M costs

Savings in O&M costs will compensate the additional cost in the first year of plant operation

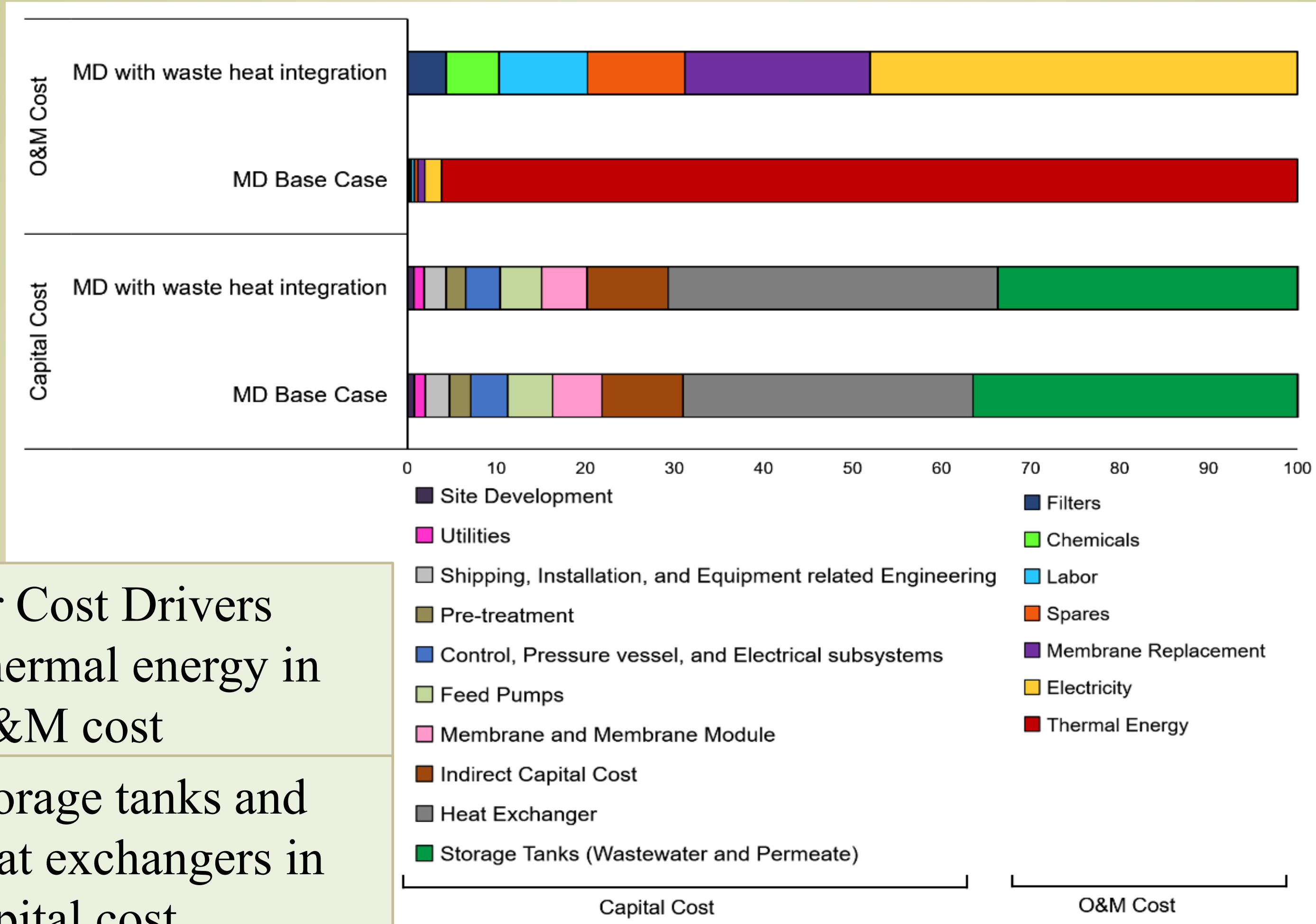
A techno-economic assessment of membrane distillation for treatment of Marcellus shale produced water, *Desalination* (under review)

Comparison with other technologies

- $1.4/m^3 for Multi Stage Flash distillation[1]
- $1/m^3 for Multiple Effect Distillation[1,2]
- $0.5/m^3 for Reverse Osmosis[3]

1. Van der Bruggen, B. *Membrane Technology*, 2003. **2003**(2): p. 6-9.
2. Wade, N.M. *Desalination*, 2001. **136**(1): p. 3-12.
3. Fritzmann, C., et al. *Desalination*, 2007. **216**(1): p. 1-76.

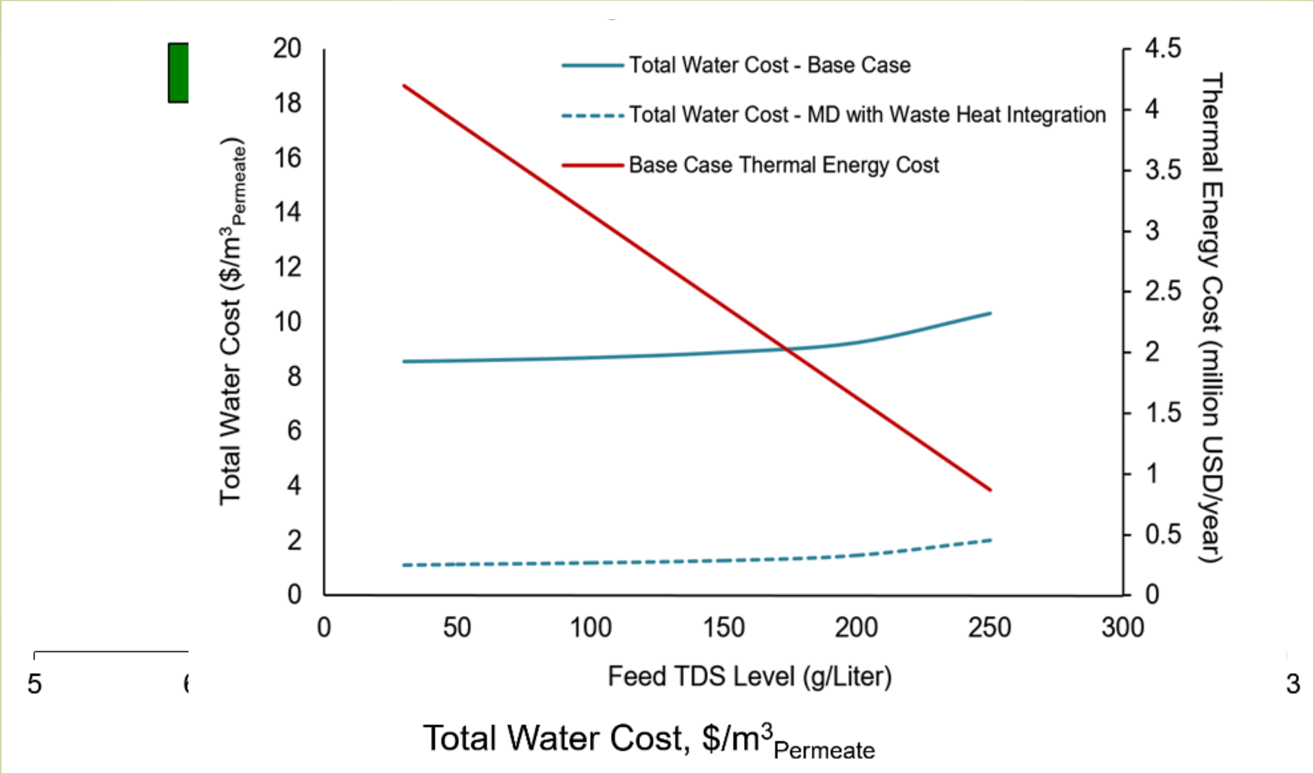
Capital and O&M Costs: Cost Components



Major Cost Drivers

- Thermal energy in O&M cost
- Storage tanks and heat exchangers in capital cost

Sensitivity Analysis



- Lower salinity produced water has higher energy demand as it needs to be recirculated more to reach 30% salinity for the reject stream
- Lower TDS results in larger volume of purified water relative to higher TDS produced water

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Conclusions

- DCMD shows potential for produced water treatment at high salinities
  - Negligible effects of membrane fouling
- Abundant high quality waste heat is available at NGCS
- Cost of DCMD treatment decreases significantly when waste heat is available
  - Comparable to competing technologies
- Produced water treatment with DCMD provides a 50% benefit over business-as-usual management strategy

Thank You

- Acknowledgments
  - U.S. DOE, National Energy Technology Laboratory