Pacific Northwest NATIONAL LABORATORY

Techno-economic Assessment of EEMPA for CO_2 Separation from Natural Gas Combined Cycle Power Plant (FWP 70814)

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Net-zero Flexible Power: High Capture Rate Project Review Meeting
Delta Hotel Philadelphia Airport, June 6-7, 2024.

U.S. DEPARTMENT OF ENERGY BATTELLE

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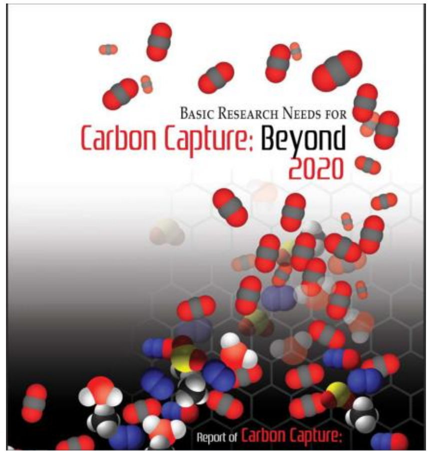
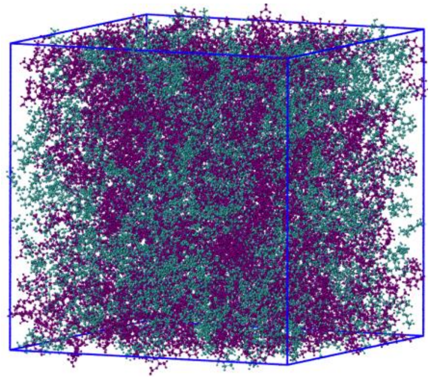
PNNL-XX-XXXX

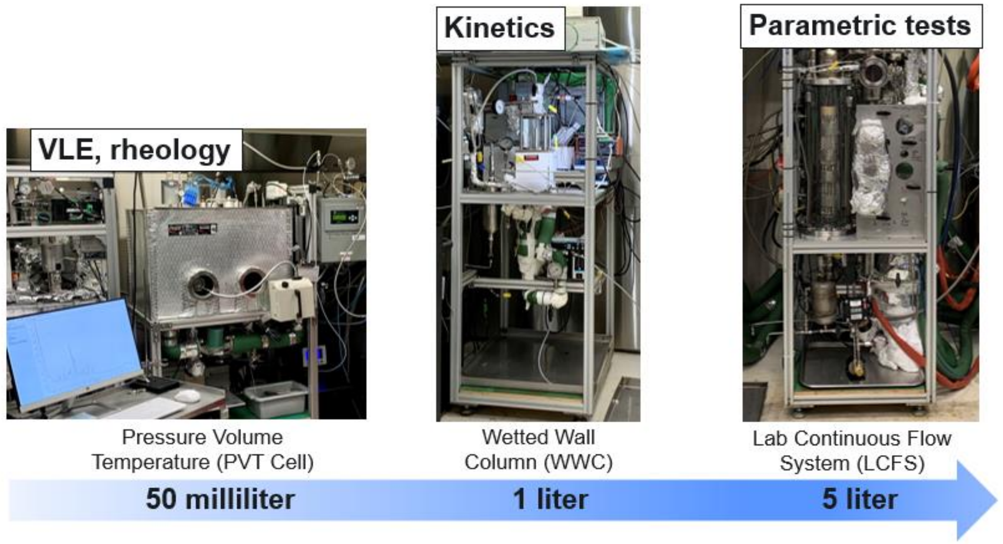
PNNL's 15-Year Effort in CCS

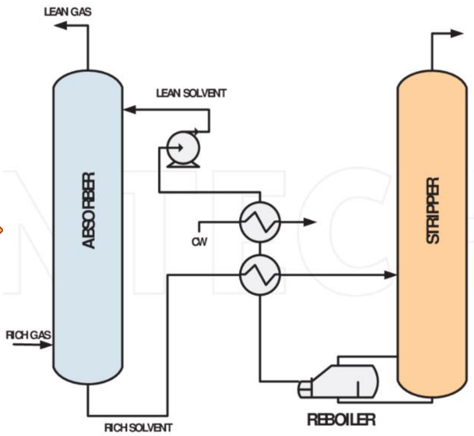
Building multi-scale, multi-disciplinary teams to bridge the knowledge gaps and reinvent solvent-based CCS from the ground up.

Fundamental research in DOE's Office of Science & Applied research in DOE's Office of Fossil Energy.









Solvent Molecular Design
Property Prediction

Synthesis, Property Measures
Performance Testing

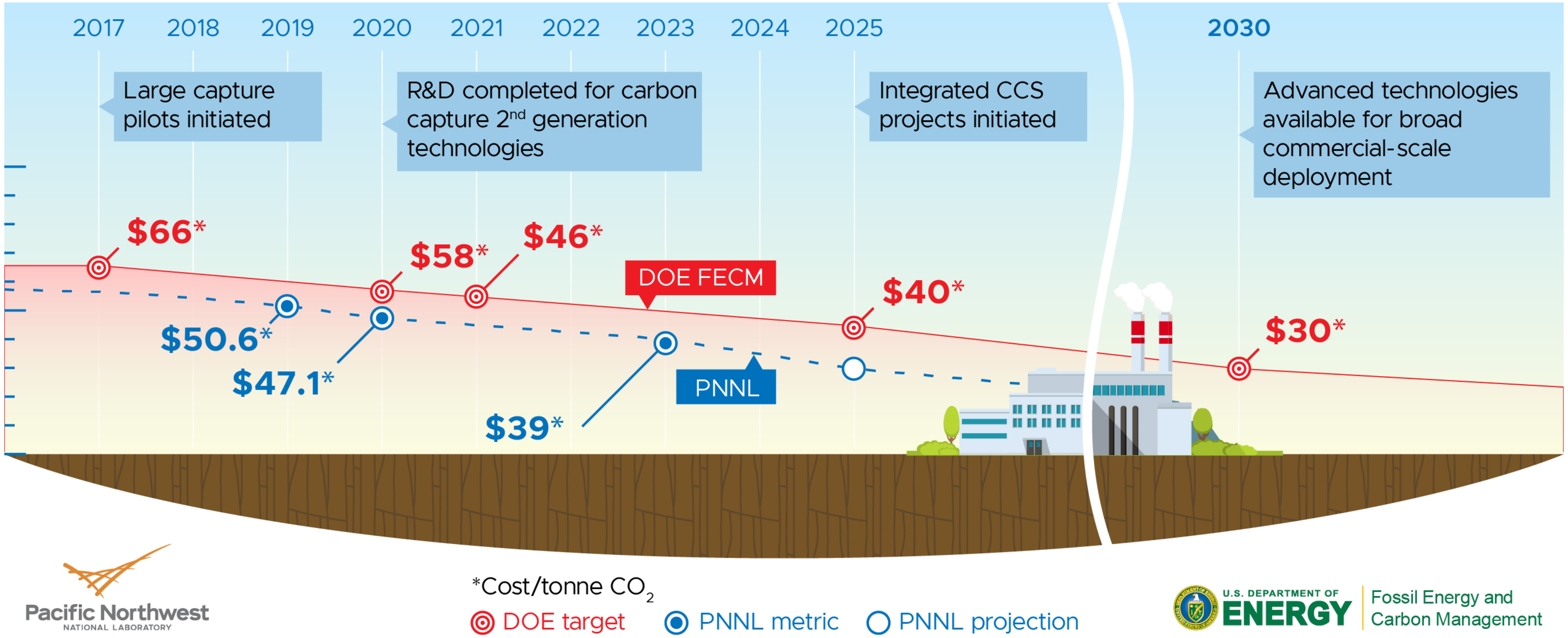
Process Design, Optimization
Techno-economic Analysis

Industry Partnership

Research Objective: Achieve Potential Step-Change Reductions in Total Costs of Capture

PNNL's goal is to make step-change progress towards the DOE target of $30/tonne CO_2 well-before year 2030.

Supercritical PC power plant



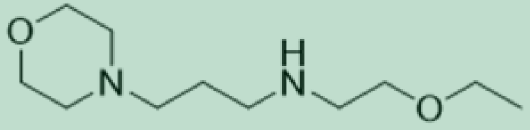
* DOE baseline REV3 pricing used until 2020, REV4 pricing implemented in 2021.

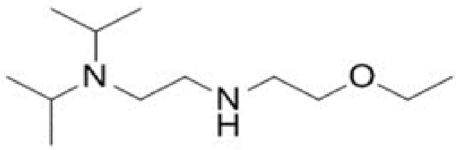
Project Overview

- **Total Project Funding**: $106k (Rescoping of remaining funds from Fluor Solvent Testing at Technology Center Mongstad)
- **Overall Project Performance Date**: 10/01/2023-09/30/2024
- **Task 1 (Completed):** Assess and publish the economic performance of PNNL's leading CO_2 capture solvent (EEMPA) for
  - Natural gas power flue gas conditions at high capture rates and
  - Potentials to achieve zero- and negative-emission comparable to DAC (100 ppmv of CO_2 in the exhaust gases)
- **Task 2 (In Progress):** Provide modeling and data support as part of a preliminary proposal for EEMPA testing at the Technology Center Mongstad (TCM)

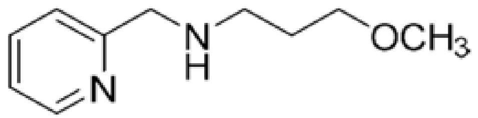
What Are CO_2BOLs (Binding Organic Liquids)?

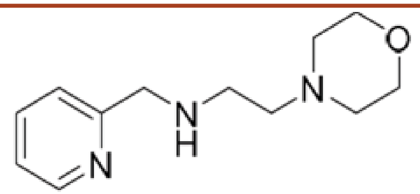
- Single-component zwitterionic liquids (when saturated with CO_2), (no blends/additives) – *simpler, lower sensible heat, faster kinetics*
- Can operate with minimal water “water lean” (1-5 wt%) – *practical water uptake from flue gas, water wash capable*
- Can exhibit viscosity increases with loading (early versions > 3000cp) *New formulations are <50 cP fully saturated with CO_2*
- Multiple chemical functionalities available– *chemical durability/toxicity are functional group dependent*
- CO_2BOLs Families


EEMPA


EEDIDA

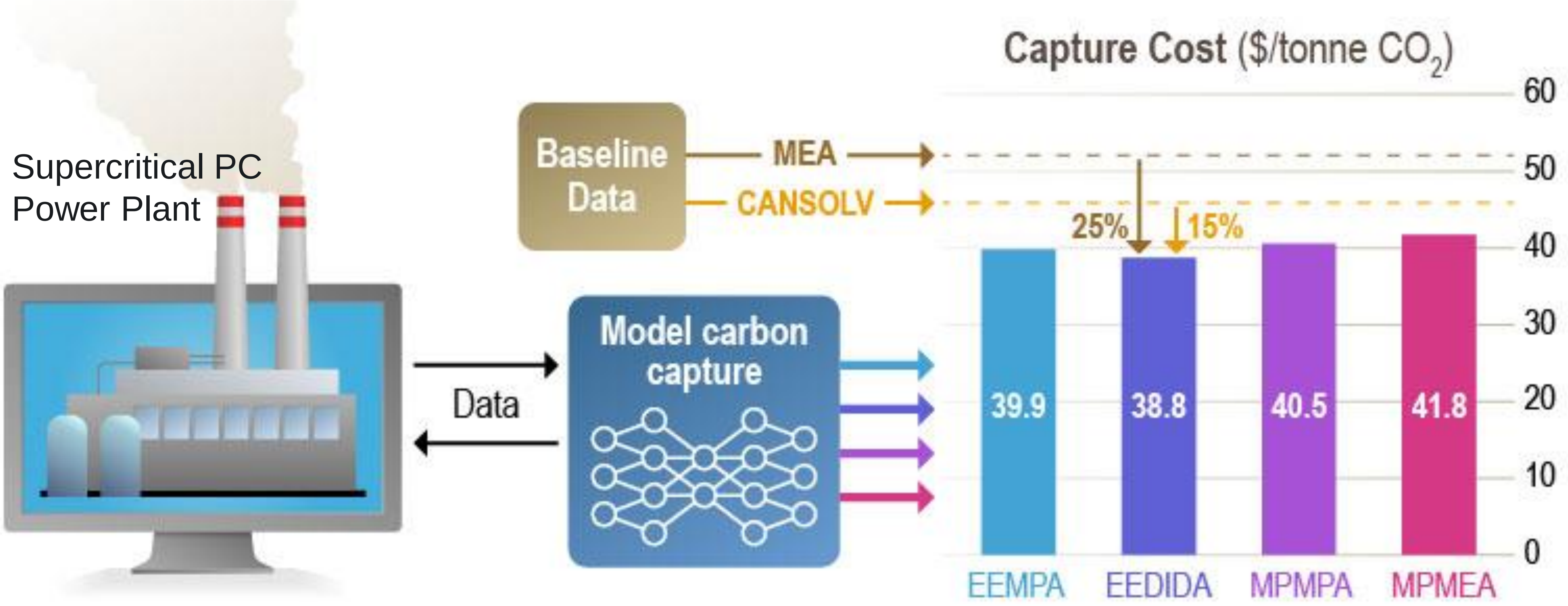
Diamines


MPMPA


MPMEA

Aminopyridines

Previous TEA Showing Cost Advantages of CO2BOLs for Coal Power Plant Applications

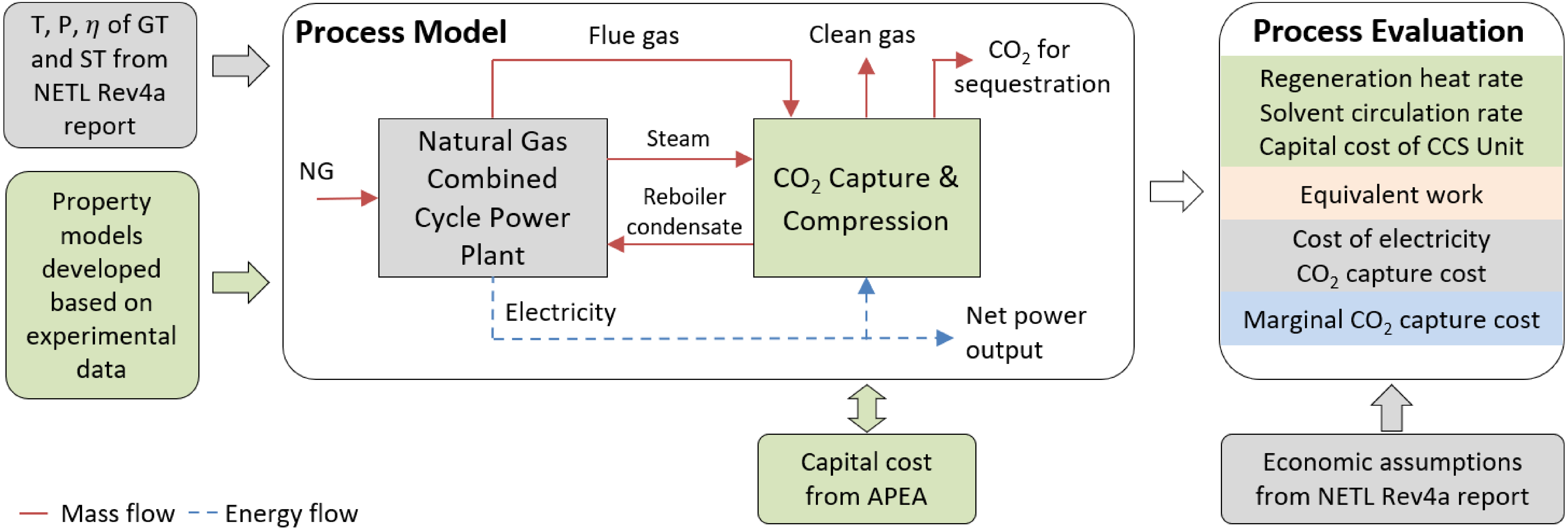


- Using similar approach to evaluate the economic feasibility of EEMPA for capturing 90%+ CO_2 from NGCC power plant

Jiang et al. (*2022*), *doi.org/10.1016/j.jclepro.2022.135696.*

Techno-economic Analysis

Using Validated Model and DOE Baseline



EEMPA models in Aspen | Method from Du et al. | Method from Van Wagener and Rochelle | Method from NETL

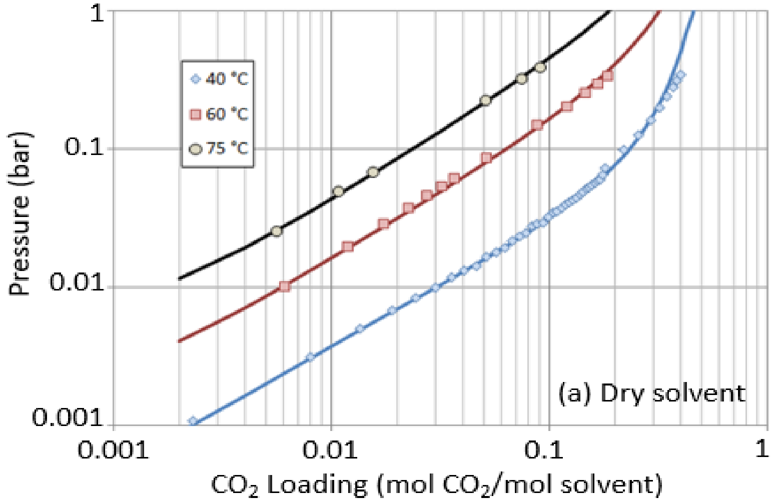
$$C_{CCS} = \frac{(COE_{CCS} - COE_{non-CCS})}{CO_2\ Captured} \qquad C_{mccs} = \frac{C_{CCS,x_2}x_2 - C_{CCS,x_1}x_1}{x_2 - x_1}$$

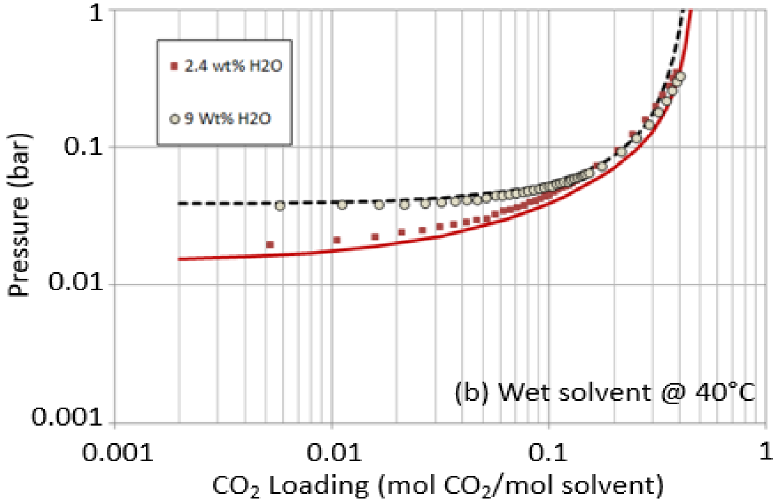
➢ **EEMPA price = $10/kg (preliminary estimate)**

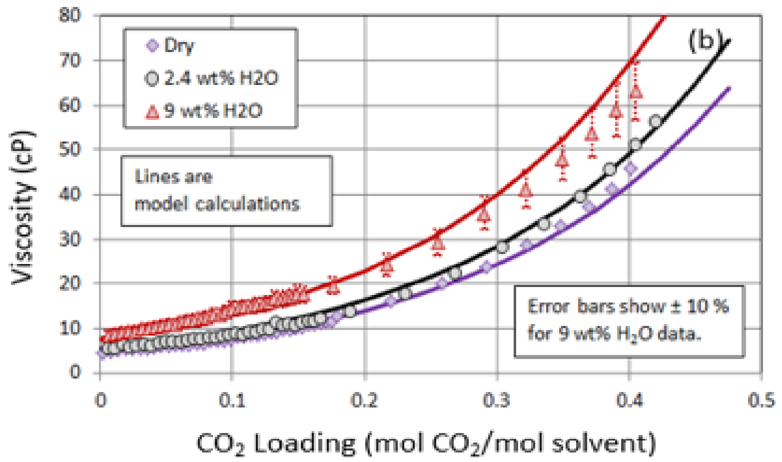
Jiang et al. *(2021), doi.org/10.1016/j.ijggc.2021.103279.*

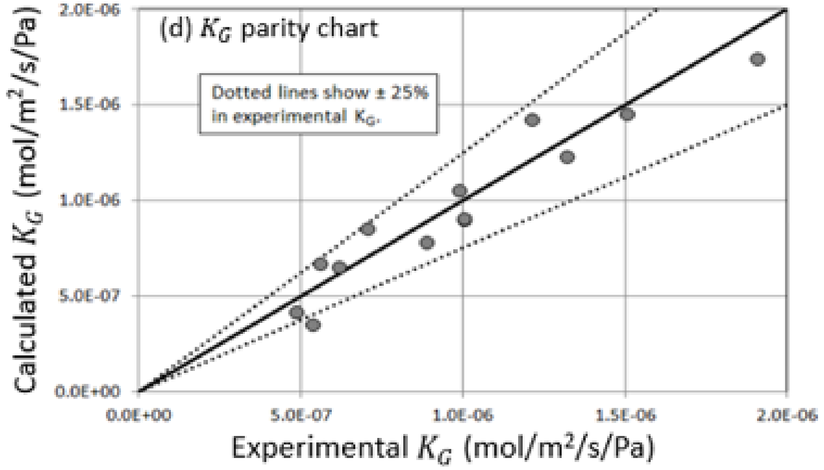
Thermodynamic Model Developed Based on Experimentally Measured Property Data

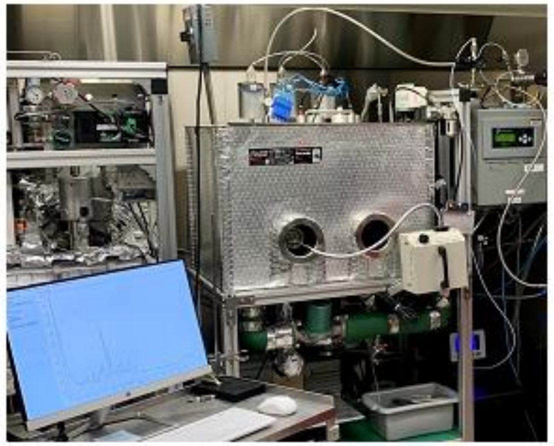
- Property Package: ENRTL-RK
- Reactions: 2 EEMPA + CO_2 ↔ $EEMPA^+$ + $EEMPACOO^-$
  EEMPA + CO_2 + H_2O ↔ $EEMPA^+$ + HCO_3^-











Pressure Volume Temperature
(PVT Cell)

Physical Properties
ρ, σ, μ(γ), FP, etc.

Wetted Wall Column
(WWC)

Jiang et al. *(2021), doi.org/10.1016/j.ijggc.2021.103279.*

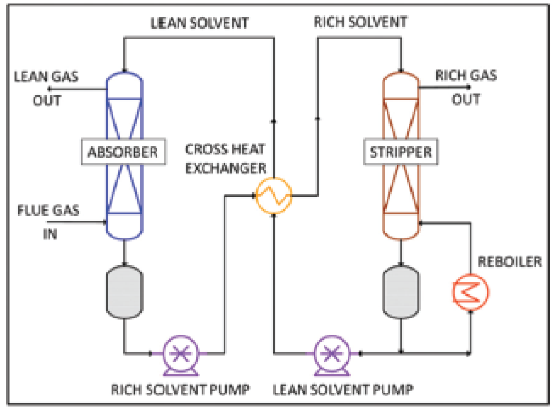
Process Model Developed in Aspen Plus and Validated Using Continuous Flow System Data

➢ Testing at PNNL's 5L LCFS

Absorber: 3” diameter, 20” height

Stripper: 3” diameter, 24” height

Packing: 0.24” Pro-Pak



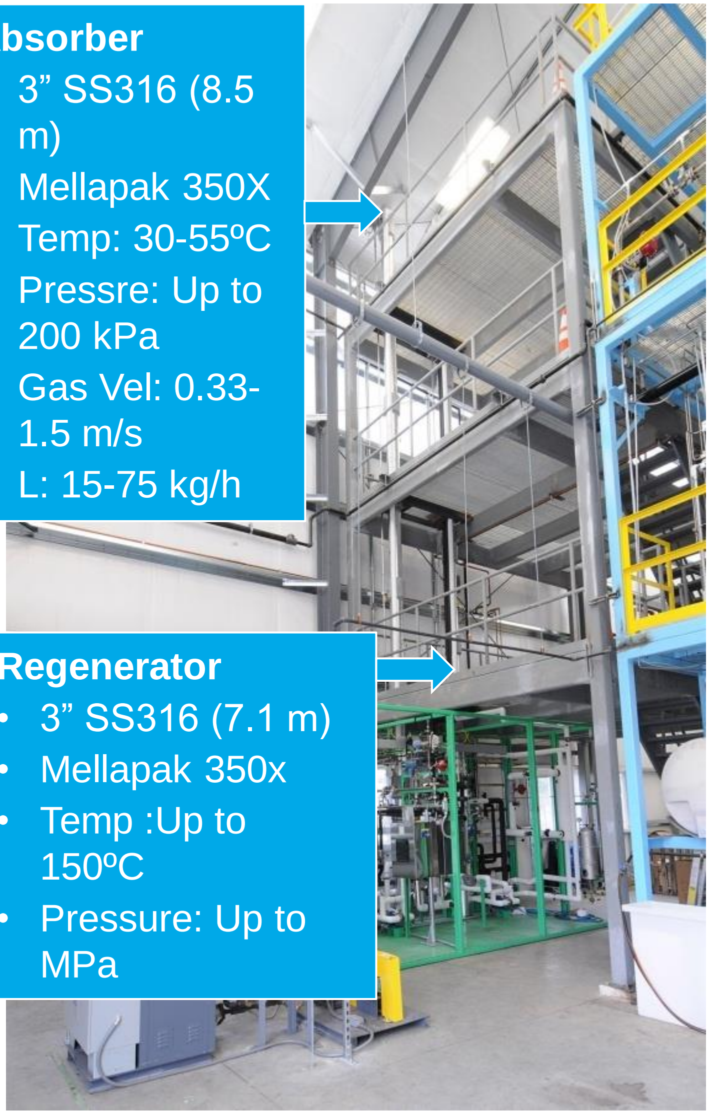
Variable	Measured	Modeled
Rich CO_2 loading (mol/mol solvent)	0.0933	0.1026
Rich H_2O loading (wt%)	0.0149	0.0139
CO_2 capture rate (%)	95.8	94.4

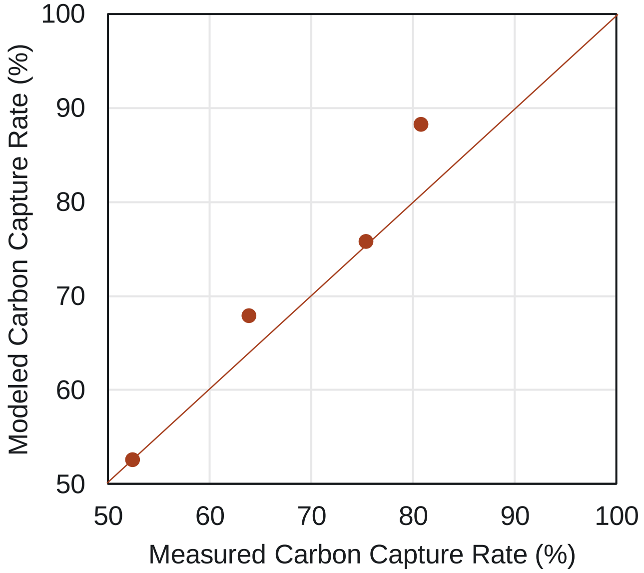
Zheng et al. *(2021), doi.org/10.1039/D0EE02585B.*

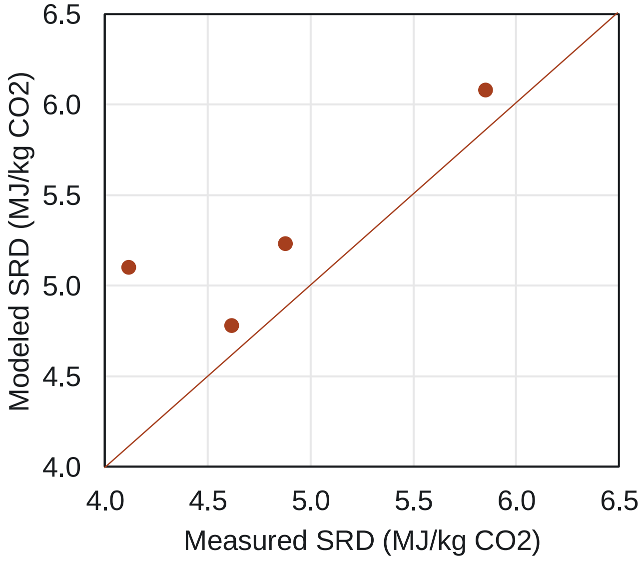
➢ Testing at RTI International's 50L BsGAS

Absorber
- 3” SS316 (8.5 m)
- Mellapak 350X
- Temp: 30-55ºC
- Pressre: Up to 200 kPa
- Gas Vel: 0.33-1.5 m/s
- L: 15-75 kg/h

Regenerator
- 3” SS316 (7.1 m)
- Mellapak 350x
- Temp :Up to 150ºC
- Pressure: Up to MPa





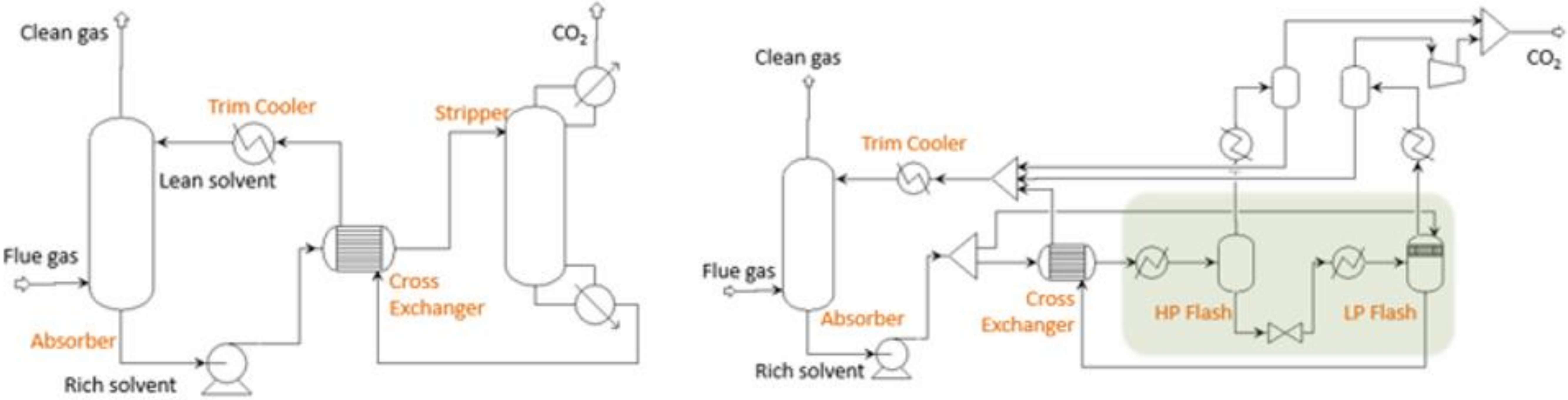


Techno-Economic Analysis

Assessing the cost and energetics of simple stripper (SS) and two-stage flash (TSF) configuration using Rev4 Case B32B baseline

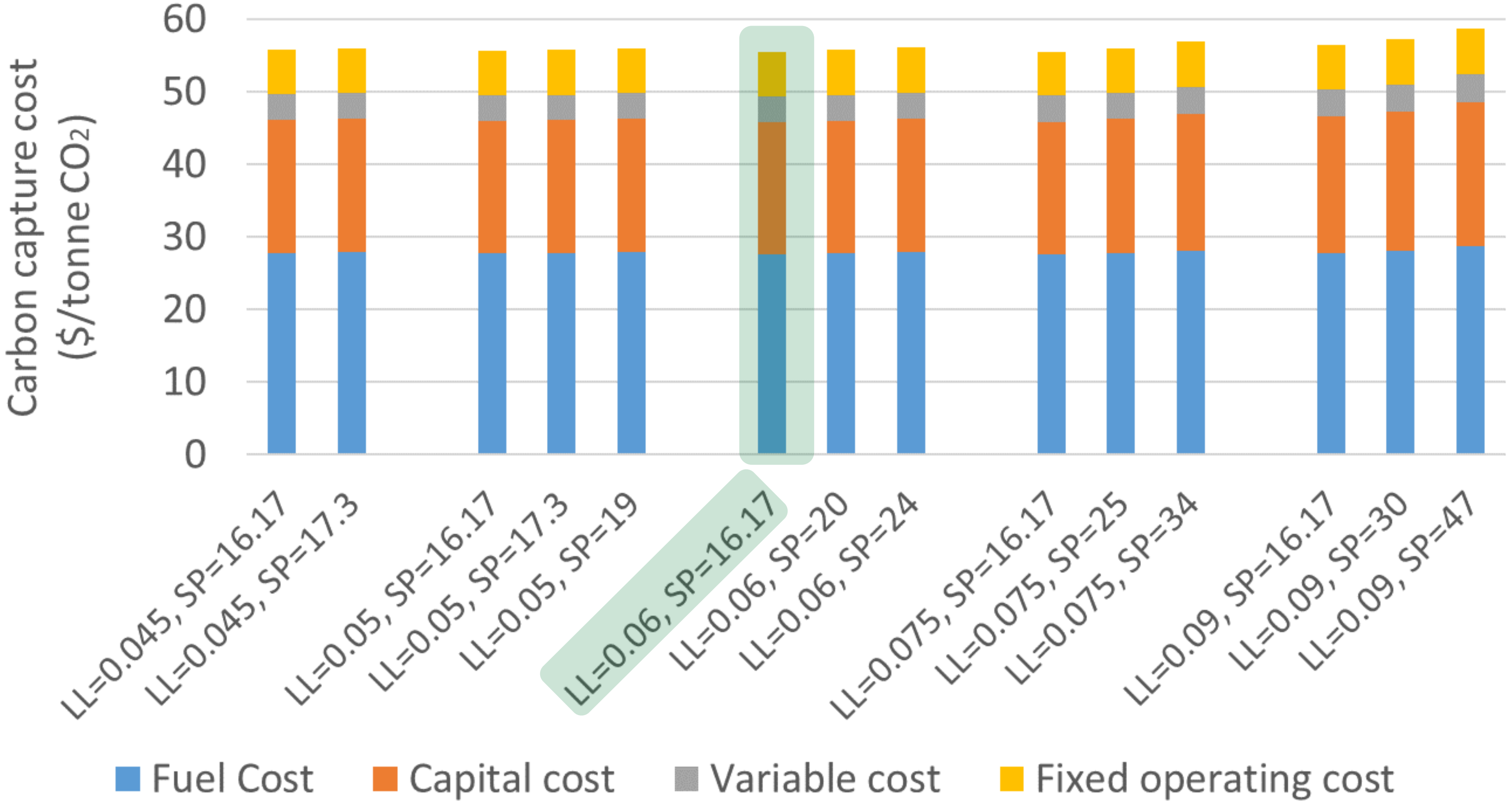
- H-Frame NGCC Cases
- Net power output = 883 MW
- Pricing basis of Dec 2018

***DOE/NETL – 2023/4320**



(a) Simple stripper (SS) (b) Two-stage flash (TSF)

Process Optimization
Example: 90% Capture with SS



- Lean loading and regeneration pressure are the top two key design variables, of which optimum varies with capture rates.
- Higher stripper pressure (SP, psi) leads to lower compression duty but higher reboiler duty and chilling duty.
- Higher lean loading (LL, mol CO_2 /mol solvent) leads to lower fuel cost but higher capital cost.

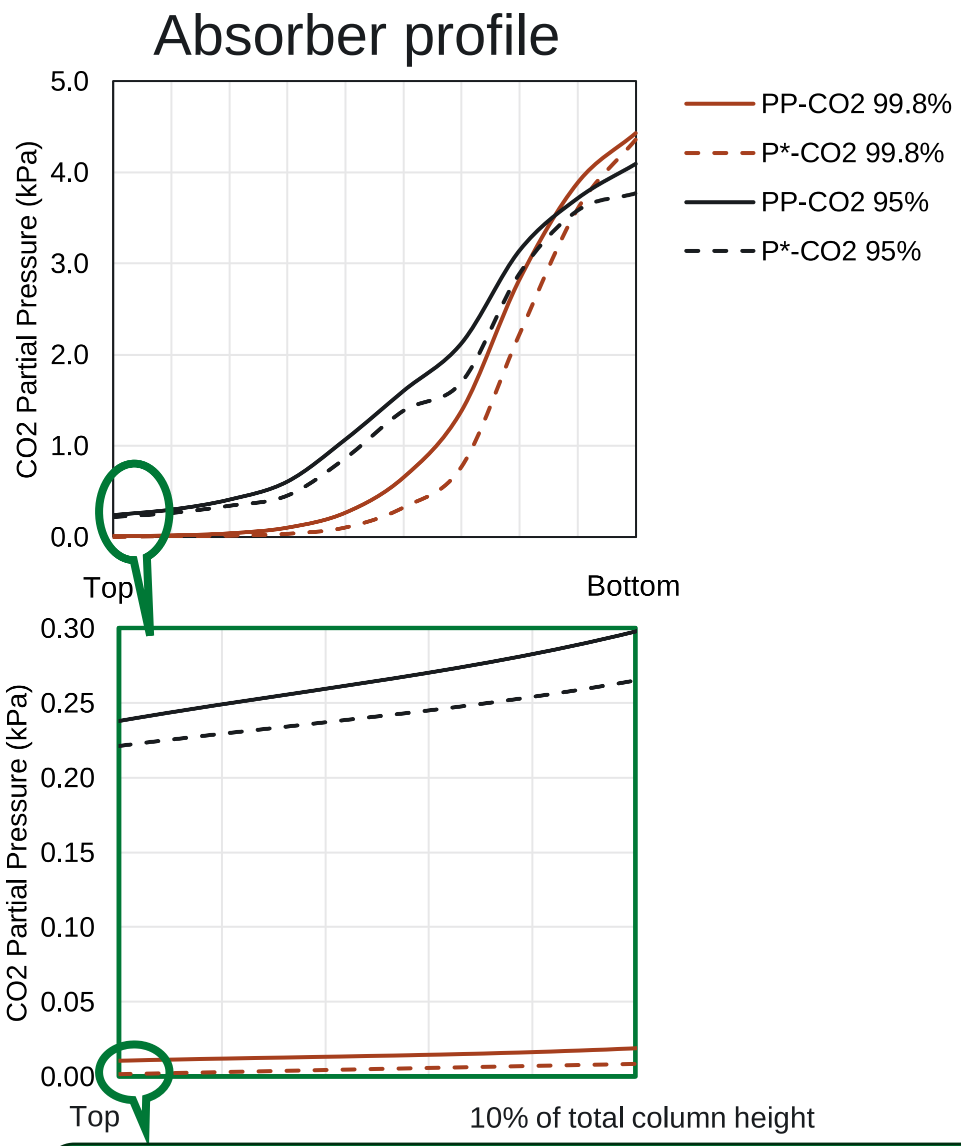
- **Higher capture rate requires:**
  - **Lower lean loading (due to VLE limitation)**
  - **Lower regeneration pressure (to keep regeneration temperature below 130 °C)**

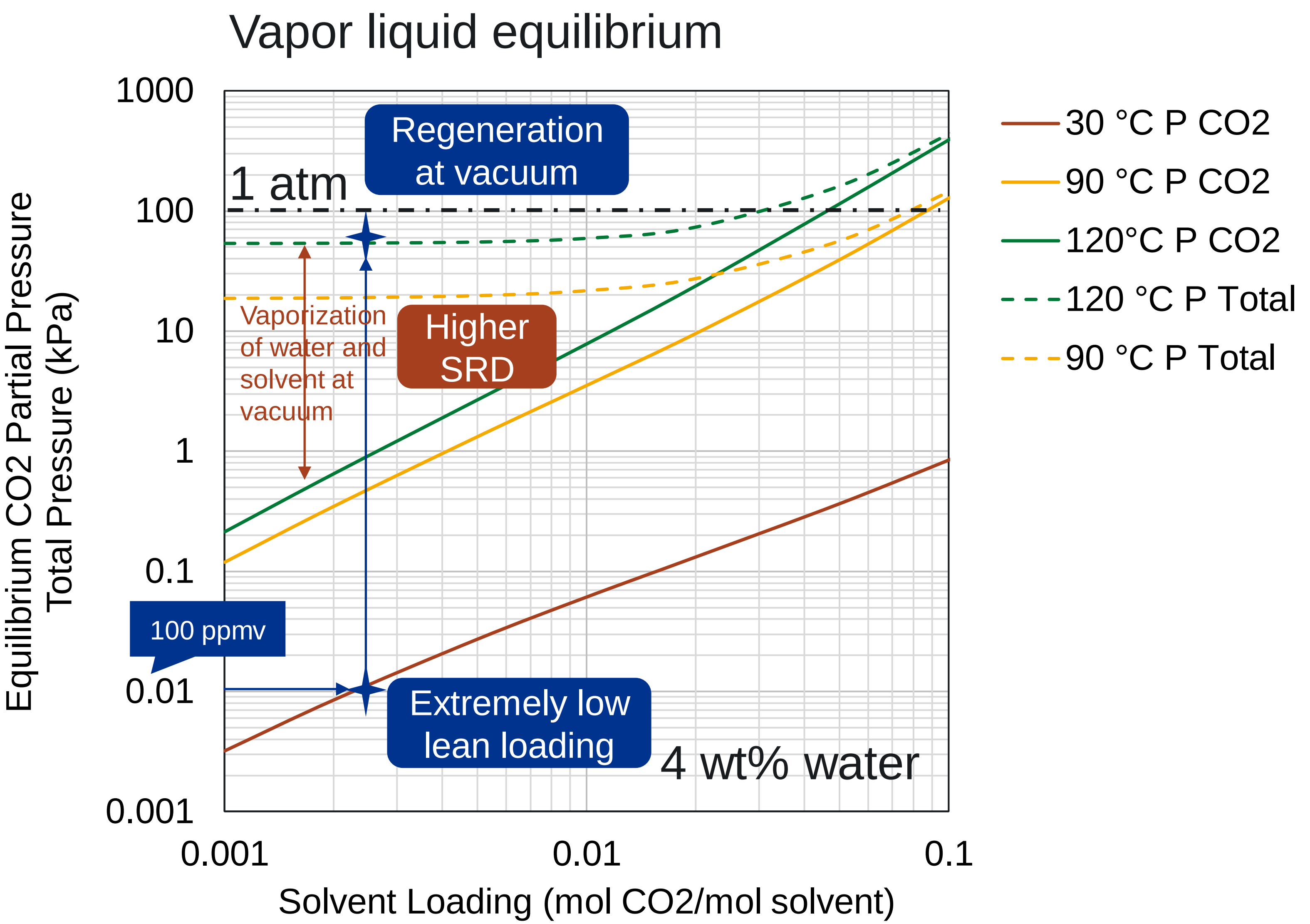
EEMPA for High Capture Rates

TEA suggests cost advantage at capture rate <95%

	Cansolv			EEMPA		
Carbon capture rate (%)	90	95	97	90	95	97
Operating condition						
Lean loading (mol CO_2/mol solvent)				0.05	0.05	0.038
Regeneration pressure (psi)				18 / 76	18 / 76	15 / 76
Flue gas chilling temperature (°C)				12.6	10.4	10.4
Performance measures						
L/G ratio (wt/wt)				2.11	2.61	3.37
Reboiler duty (GJ/tonne CO_2)	2.90	2.89	2.97	2.67	2.73	3.16
Equivalent work (kJ/mol CO_2)						
Reboiler	30.3	30.2	31.0	23.8	24.3	28.2
Compression	13.0	13.0	13.0	11.8	12.1	14.1
Total	50.2	50.3	51.6	44.7	46.4	52.9
Economic measures (2018 pricing basis)						
Total plant cost of CCS (MM$)	496	517	529	500	548	621
Cost of electricity ($/MWe-hr)	61.6	62.5	63.1	60	61.3	62.8
Carbon capture cost ($/tonne CO_2)	56	55.3	55.5	53	53.4	56.4

EEMPA for achieving < 100 ppmv CO_2 in clean flue gas comparable to DAC – VLE Limitation





Extremely low solvent lean loading is required to achieve 99.8% CO2 removal, which results in expensive solvent regeneration. A combination of both temperature and pressure swing regeneration is required.

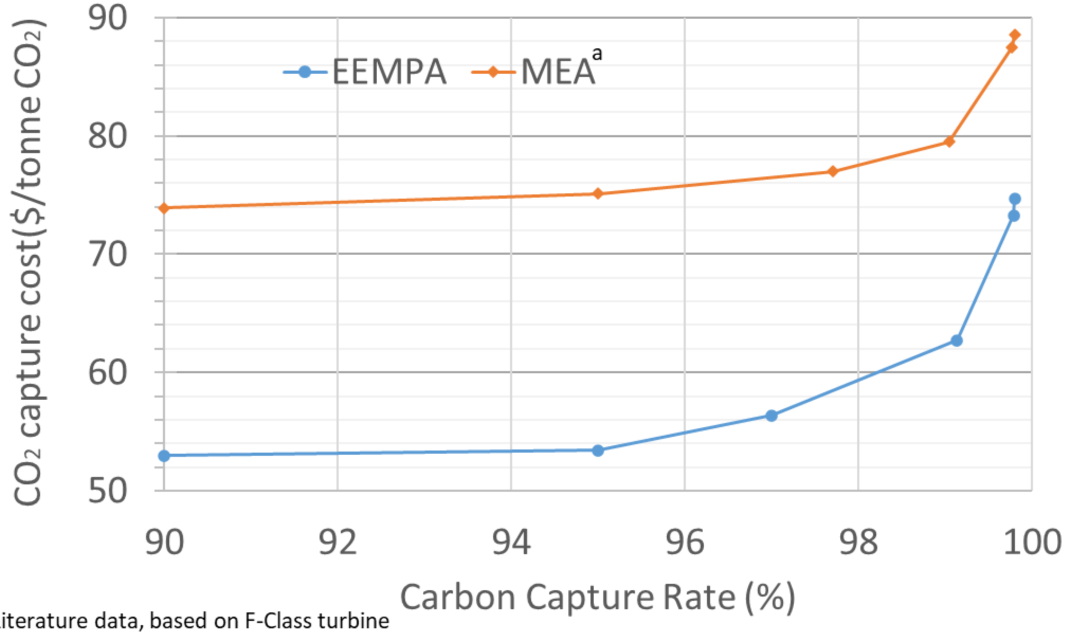
EEMPA for Zero- and Negative-Emissions NGCC Plants and Comparison with MEA

Carbon capture cost

- Represents an **average cost** of reducing CO_2 concentration **from a starting point** (4% in NGCC flue gas) to **a targeted capture rate**
- Is a key economic metric for evaluating **post combustion carbon capture** and comparing different technologies with the **same starting and ending** CO_2 concentration

	Capture rate (%)	90	95	97	99.14	99.78	99.80
MEA	Carbon capture cost (\$/tonne CO_2)	73.9	75.1	77.0	79.5	87.5	88.6
EEMPA	Carbon capture cost (\$/tonne CO_2)	53.0	53.4	56.4	62.7	73.3	74.7

EEMPA has much **lower capture cost** than MEA from 90% capture rate to zero- and negative-emissions.



[a]Literature data, based on F-Class turbine

EEMPA for Zero- and Negative-Emissions NGCC Plants and Comparison with DAC

Marginal carbon capture cost

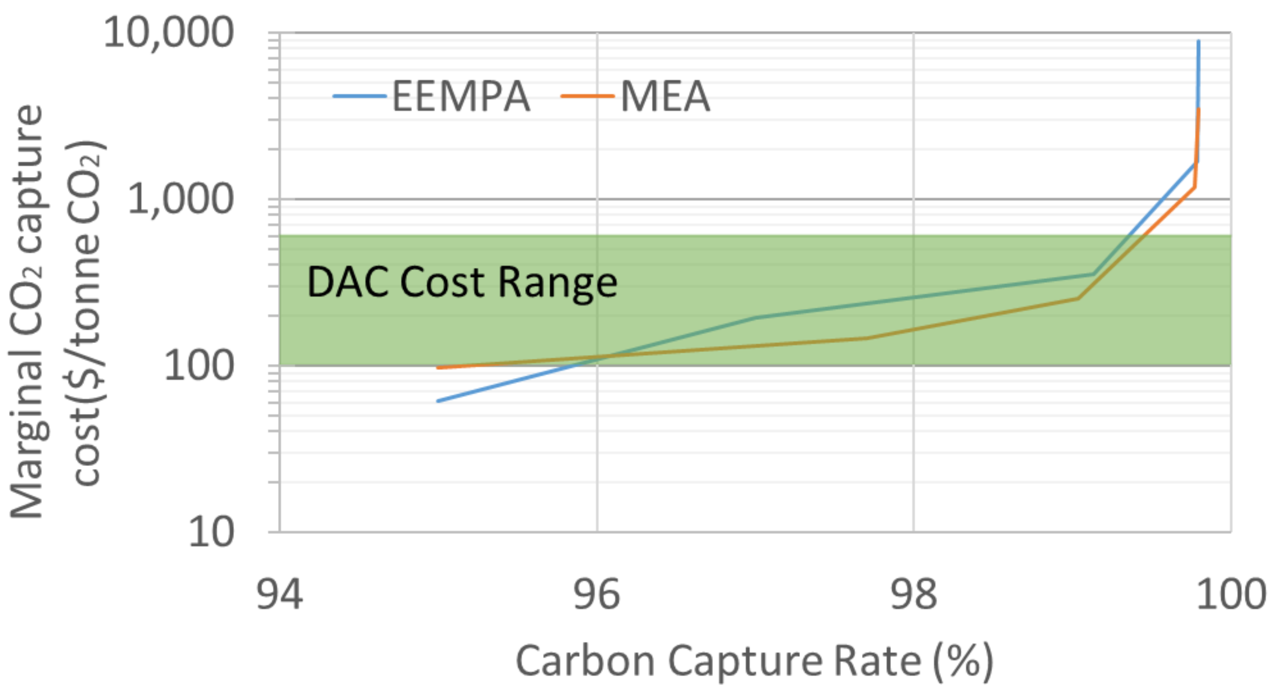
- Represents the **rate of change** in carbon capture cost for **each additional amount** of CO_2 captured (i.e. from 400 ppm to 100ppm CO_2 in the exhaust gas).
- Is a key economic metric for comparing **post combustion carbon capture** with **direct air capture,** of which starting points are quite different (4% vs 400 ppm).

	Capture rate (%)	95	97	99.14	99.78	99.80
MEA	Marginal cost (\$/tonne CO_2)	96.7	143.9	261.8	1,173	3,747
EEMPA	Marginal cost (\$/tonne CO_2)	61.5	194.9	351.4	1,691	8,868

$$Marginal\ cost\Big|_{x2} = \frac{\partial C}{\partial x}\Big|_{x2} \approx \frac{C_{x2} * x_2 - C_{x1} * x_1}{x_2 - x_1}$$

x=CO_2 capture (%); x_2 is a higher level of CO_2 capture than x_1

Both MEA and EEMPA were not designed and optimized for achieving 100 ppmv CO_2 in exhaust gas.



Challenges and R&D Needs for high capture rate & flexible operation

- Optimization
- Intensification
- Integration
- Dynamic control

Questions
&
Discussion

The authors would like to acknowledge the US Department of Energy Office of Fossil Energy FWP 70814 (managed by NETL) for funding this project and the Pacific Northwest National Laboratory (PNNL) for facilities. The authors would also like to thank Robert Perry for insights into diamine behavior and fruitful discussions. Battelle proudly operates PNNL for DOE under Contract DE-AC05-76RL01830.